Also, as shown in conveyor application of Fig. 1B3, the height dimension of the planar laser illumination beam (PLIB) is substantially greater than the height dimension of the magnified field of view (FOV) of each image detection element in the linear CCD image detection array. The reason for this condition between the PLIB and the FOV is to decrease the range of tolerance which must be maintained when the PLIB and the FOV are aligned in a coplanar relationship along the entire working distance of the PLIIM-based system.

When the laser beam is fanned (i.e. spread) out into a substantially planar laser illumination beam by the cylindrical lens element employed within each PLIM in the PLIIM system, the total output power in the planar laser illumination beam is distributed along the width of the beam in a roughly Gaussian distribution, as shown in the power vs. position plot of Fig. 1M2. Notably, this plot was constructed using actual data gathered with a planar laser illumination beam focused at the farthest object distance in the PLIIM system. For comparison purposes, the data points and a Gaussian curve fit are shown for the planar laser beam widths taken at the nearest and farthest object distances. To avoid having to consider two dimensions simultaneously (i.e. left-to-right along the planar laser beam width dimension and near-to-far through the object distance dimension), the discussion below will assume that only a single pixel is under consideration, and that this pixel views the target object at the center of the planar laser beam width.

For a fixed focal length imaging lens, the width L of the planar laser beam is a function of the fan/spread angle θ induced by (i) the cylindrical lens element in the PLIM and (ii) the object distance r, as defined by the following expression (9):

$$L = 2r \tan\frac{\theta}{2} \qquad (9)$$

Fig. 1M3 shows a plot of beam width length L versus object distance r calculated using θ = 50°, demonstrating the planar laser beam width increases as a function of increasing object distance.

The height parameter of the planar laser illumination beam "h" is controlled by adjusting the focusing lens 15 between the visible laser diode (VLD) 13 and the cylindrical lens 16, shown in Figs. 1I1 and 1I2. Fig. 1M4 shows a typical plot of planar laser beam height h vs. image distance r for a planar laser illumination beam focused at the farthest object distance in accordance with the principles of the present invention. As shown in Fig. 1M4, the height dimension of the planar laser beam decreases as a function of increasing object distance.

Assuming a reasonable total laser power output of 20 mW from the VLD 13 in each PLIM 11, the values shown in the plots of Figs. 1M3 and 1M4 can be used to determine the power density E_0 of the planar laser beam at the center of its beam width, expressed as a function of object distance. This measure, plotted in Fig. 1N, demonstrates that the use of the laser beam focusing technique of the present invention, wherein the height of the planar laser illumination beam is decreased as the object distance increases, compensates for the increase in beam width in the planar laser illumination beam, which occurs for an increase in object distance. This yields a laser beam power density on the target object which increases as a function of increasing object distance over a substantial portion of the object distance range of the PLIIM system.

Finally, the power density E_0 plot shown in Fig. 1N can be used with expression (1) above to determine the power density on the pixel, E_{pix}. This E_{pix} plot is shown in Fig. 1O. For comparison purposes, the plot obtained when using the beam focusing method of the present invention is plotted in Fig. 1O against a "reference" power density plot E_{pix} which is obtained when focusing the laser beam at infinity, using a collimating lens (rather than a focusing lens 15) disposed after the VLD 13, to produce a collimated-type planar laser illumination beam having a constant beam height of 1 mm over the entire portion of the object distance range of the system. Notably, however, this non-preferred beam collimating technique, selected as the reference plot in Fig. 1O, does not compensate for the above-described effects associated with an increase in planar laser beam width as a function of object distance. Consequently, when using this non-preferred beam focusing technique, the power density of the planar laser illumination beam produced by each PLIM decreases as a function of increasing object distance.

Therefore, in summary, where a fixed or variable focal length imaging subsystem is employed in the PLIIM system hereof, the planar laser beam focusing technique of the present invention described above helps compensate for decreases in the power density of the incident planar illumination beam due to the fact that the width of the planar laser illumination beam increases for increasing object distances away from the imaging subsystem.

<u>Producing A Composite Planar Laser Illumination Beam Having Substantially Uniform Power Density Characteristics In Near And Far Fields, By Additively Combining The Individual Gaussian Power Density Distributions Of Planar Laser Illumination Beams Produced By Planar Laser Illumination Beam Modules (PLIMS) In Planar Laser Illumination Arrays (PLIAs)</u>

Having described the best known method of focusing the planar laser illumination beam produced by each VLD in each PLIM in the PLIIM-based system hereof, it is appropriate at this juncture to describe how the individual Gaussian power density distributions of the planar laser illumination beams produced a PLIA 6A, 6B are additively combined to produce a

composite planar laser illumination beam having substantially uniform power density characteristics in near and far fields, as illustrated in Figs. 1P1 and 1P2.

When the laser beam produced from the VLD is transmitted through the cylindrical lens, the output beam will be spread out into a laser illumination beam extending in a plane along the direction in which the lens has curvature. The beam size along the axis which corresponds to the height of the cylindrical lens will be transmitted unchanged. When the planar laser illumination beam is projected onto a target surface, its profile of power versus displacement will have an approximately Gaussian distribution. In accordance with the principles of the present invention, the plurality of VLDs on each side of the IFD module are spaced out and tilted in such a way that their individual power density distributions add up to produce a (composite) planar laser illumination beam having a magnitude of illumination which is distributed substantially uniformly over the entire working depth of the PLIIM-based system (i.e. along the height and width of the composite planar laser illumination beam).

The actual positions of the PLIMs along each planar laser illumination array are indicated in Fig. 1G3 for the exemplary PLIIM-based system shown in Figs. 1G1 through 1I2. The mathematical analysis used to analyze the results of summing up the individual power density functions of the PLIMs at both near and far working distances was carried out using the Matlab™ mathematical modeling program by Mathworks, Inc. (http://www.mathworks.com). These results are set forth in the data plots of Figs. 1P1 and 1P2. Notably, in these data plots, the total power density is greater at the far field of the working range of the PLIIM system. This is because the VLDs in the PLIMs are focused to achieve minimum beam width thickness at the farthest object distance of the system, whereas the beam height is somewhat greater at the near field region. Thus, although the far field receives less illumination power at any given location, this power is concentrated into a smaller area, which results in a greater power density within the substantially planar extent of the planar laser illumination beam of the present invention.

When aligning the individual planar laser illumination beams (i.e. planar beam components) produced from each PLIM, it will be important to ensure that each such planar laser illumination beam spatially coincides with a section of the FOV of the imaging subsystem, so that the composite planar laser illumination beam produced by the individual beam components spatially coincides with the FOV of the imaging subsystem throughout the entire working depth of the PLIIM-based system.

Methods Of Reducing The RMS Power Of Speckle-Noise Patterns Observed At The Linear Image Detection Array Of A PLIIM-Based System When Illuminating Objects Using A Planar Laser Illumination Beam

In the PLIIM-based systems disclosed herein, seven (7) general classes of techniques and apparatus have been developed to effectively destroy or otherwise substantially reduce the spatial and/or temporal coherence of the laser illumination sources used to generate planar laser illumination beams (PLIBs) within such systems, and thus enable time-varying speckle-noise patterns to be produced at the image detection array thereof and temporally (and possibly spatially) averaged over the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed (i.e. detected) at the image detection array.

In general, the root mean square (RMS) power of speckle-noise patterns in PLIIM-based systems can be reduced by using any combination of the following techniques: (1) by using a multiplicity of real laser (diode) illumination sources in the planar laser illumination arrays (PLIIM) of the PLIIM-based system and cylindrical lens array 299 after each PLIA to optically combine and project the planar laser beam components from these real illumination sources onto the target object to be illuminated, as illustrated in the various embodiments of the present invention disclosed herein; and/or (2) by employing any of the seven generalized speckle-pattern noise reduction techniques of the present invention described in detail below which operate by generating independent virtual sources of laser illumination to effectively reduce the spatial and/or temporal coherence of the composite PLIB either transmitted to or reflected from the target object being illuminated. Notably, the speckle-noise reduction coefficient of the PLIIM-based system will be proportional to the square root of the number of statistically independent real and virtual sources of laser illumination created by the speckle-noise pattern reduction techniques employed within the PLIIM-based system.

In Figs. 1I1 through 1I12D, a first generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the spatial coherence of the PLIB before it illuminates the target (i.e. object) by applying spatial phase modulation techniques during the transmission of the PLIB towards the target.

In Figs. 1I13 through 1I15C, a second generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the temporal coherence of the PLIB before it illuminates the target (i.e. object) by applying temporal intensity modulation techniques during the transmission of the PLIB towards the target.

In Figs. 1I16 through 1I17E, a third generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of

apparatus therefor are schematically illustrated. This generalized method involves reducing the temporal coherence of the PLIB before it illuminates the target (i.e. object) by applying temporal phase modulation techniques during the transmission of the PLIB towards the target.

In Figs. 1I18 through 1I19C, a fourth generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the spatial coherence of the PLIB before it illuminates the target (i.e. object) by applying temporal frequency modulation (e.g. compounding/complexing) during transmission of the PLIB towards the target.

In Figs. 1I20 through 1I21D, a fifth generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the spatial coherence of the PLIB before it illuminates the target (i.e. object) by applying spatial intensity modulation techniques during the transmission of the PLIB towards the target.

In Figs. 1I22 through 1I23B, a sixth generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the spatial coherence of the PLIB after the transmitted PLIB reflects and/or scatters off the illuminated the target (i.e. object) by applying spatial intensity modulation techniques during the detection of the reflected/scattered PLIB.

In Figs. 1I24 through 1I24C, a seventh generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the temporal coherence of the PLIB after the transmitted PLIB reflects and/or scatters off the illuminated the target (i.e. object) by applying spatial intensity modulation techniques during the detection of the reflected/scattered PLIB.

In Figs. 1I25A through 1I25N2, various "hybrid" despeckling methods and apparatus are disclosed for use in conjunction with PLIIM-based systems employing linear (or area) electronic image detection arrays having elongated image detection elements with a high height-to-width (H/W) aspect ratio.

Notably, each of the seven generalized methods of speckle-noise pattern reduction to be described below are assumed to satisfy the general conditions under which the random "speckle-noise" process is Gaussian in character. These general conditions have been clearly identified by J.C. Dainty, et al, in page 124 of "Laser Speckle and Related Phenomena", supra, and are restated below for the sake of completeness: (i) that the standard deviation of the surface height fluctuations in the scattering surface (i.e. target object) should be greater than λ,

thus ensuring that the phase of the scattered wave is uniformly distributed in the range 0 to 2π; and (ii) that a great many independent scattering centers (on the target object) should contribute to any given point in the image detected at the image detector.

First Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Spatial-Coherence Of The Planar Laser Illumination Beam Before It Illuminates The Target Object By Applying Spatial Phase Modulation Techniques During The Transmission Of The PLIB Towards The Target

Referring to Figs. 1I1 through 1I11C, the first generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of spatially modulating the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object (e.g. package) therewith so that the object is illuminated with a spatially coherent-reduced planar laser beam and, as a result, numerous substantially different time-varying speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array (in the IFD subsystem), thereby allowing these speckle-noise patterns to be temporally averaged and possibly spatially averaged over the photo-integration time period and the RMS power of observable speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

Whether any significant spatial averaging can occur in any particular embodiment of the present invention will depend on the relative dimensions of: (i) each element in the image detection array; and (ii) the physical dimensions of the speckle blotches in a given speckle-noise pattern which will depend on the standard deviation of the surface height fluctuations in the scattering surface or target object, and the wavelength of the illumination source λ. As the size of each image detection element is made larger, the image resolution of the image detection array will decrease, with an accompanying increase in spatial averaging. Clearly, there is a tradeoff to be decided upon in any given application.

As illustrated at Block A in Fig. 1I2B, the first step of the first generalized method shown in Figs. 1I1 through 1I11C involves spatially phase modulating the transmitted planar laser illumination beam (PLIB) along the planar extent thereof according to a (random or periodic) spatial phase modulation function (SPMF) prior to illumination of the target object with the PLIB, so as to modulate the phase along the wavefront of the PLIB and produce numerous substantially different time-varying speckle-noise pattern at the image detection array of the IFD Subsystem during the photo-integration time period thereof. As indicated at Block B in Fig. 1I2B, the second step of the method involves temporally and spatially averaging the numerous

substantially different speckle-noise patterns produced at the image detection array in the IFD Subsystem during the photo-integration time period thereof.

When using the first generalized method, the target object is repeatedly illuminated with laser light apparently originating from different points (i.e. virtual illumination sources) in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered spatially incoherent with each other. On a time-average basis, these time-varying speckle-noise patterns are temporally (and possibly spatially) averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of the speckle-noise pattern (i.e. level) observed thereat. As speckle noise patterns are roughly uncorrelated at the image detection array, the reduction in speckle-noise power should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the image frame thereof. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The first generalized method above can be explained in terms of Fourier Transform optics. When spatial phase modulating the transmitted PLIB by a periodic or random spatial phase modulation function (SPMF), while satisfying conditions (i) and (ii) above, a spatial phase modulation process occurs on the spatial domain. This spatial phase modulation process is equivalent to mathematically multiplying the transmitted PLIB by the spatial phase modulation function. This multiplication process on the spatial domain is equivalent on the spatial-frequency domain to the convolution of the Fourier Transform of the spatial phase modulation function with the Fourier Transform of the transmitted PLIB. On the spatial-frequency domain, this convolution process generates spatially-incoherent (i.e. statistically-uncorrelated) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally (and possibly) spatially averaged during the photo-integration time period of each detector element, to reduce the RMS power of the speckle-noise pattern observed at the image detection array.

In general, various types of spatial phase modulation techniques can be used to carry out the first generalized method including, for example: mechanisms for moving the relative position/motion of a cylindrical lens array and laser diode array, including reciprocating a pair of rectilinear cylindrical lens arrays relative to each other, as well as rotating a cylindrical lens

array ring structure about each PLIM employed in the PLIIM-based system; rotating phase modulation discs having multiple sectors with different refractive indices to effect different degrees of phase delay along the wavefront of the PLIB transmitted (along different optical paths) towards the object to be illuminated; acousto-optical Bragg-type cells for enabling beam steering using ultrasonic waves; ultrasonically-driven deformable mirror structures; a LCD-type spatial phase modulation panel; and other spatial phase modulation devices. Several of these spatial light modulation (SLM) mechanisms will be described in detail below.

<u>Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Refractive Cylindrical Lens Arrays To Spatial Phase Modulate The Planar Laser Illumination Beam Prior To Target Object Illumination</u>

In Figs. 1I3A through 1I3D, there is shown an optical assembly 300 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 300 comprises a PLIA 6A, 6B with a pair of refractive-type cylindrical lens arrays 301A and 301B, and an electronically-controlled mechanism 302 for micro-oscillating the pair cylindrical lens arrays 301A and 301B along the planar extent of the PLIB. In accordance with the first generalized method, the pair of cylindrical lens arrays 301A and 301B are micro-oscillated, relative to each other (out of phase by 90 degrees) using two pairs of ultrasonic (or other motion-imparting) transducers 303A, 303B, and 304A, 304B arranged in a push-pull configuration. The individual beam components within the PLIB 305 which are transmitted through the cylindrical lens arrays are micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity v(t) which causes the spatial phase along the wavefronts of the transmitted PLIB to be modulated and numerous (e.g. 25 or more) substantially different time-varying speckle-noise patterns generated at the image detection array of the IFD Subsystem during the photo-integration time period thereof. The numerous time-varying speckle-noise patterns produced at the image detection array are temporally (and possibly spatially) averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I3C, an array support frame 305 with a light transmission window 306 and accessories 307A and 307B for mounting pairs of ultrasonic transducers 303A, 303B and 304A, 304B, is used to mount the pair of cylindrical lens arrays 301A and 301B in a relative reciprocating manner, and thus permitting micro-oscillation in accordance with the principles of the present invention. In 1I3D, the pair of cylindrical lens arrays 301A and 301B are shown configured between pairs of ultrasonic transducers 303A, 303B and 304A, 304B (or flexural elements driven by voice-coil type devices) operated in a push-pull mode of operation. By employing dual cylindrical lens arrays in this optically assembly, the transmitted PLIB is spatial

phase modulated in a continual manner during object illumination operations. The function of cylindrical lens array 301B is to optically combine the spatial phase modulated PLIB components so that each point on the surface of the target object being illuminated by numerous spatial-phase delayed PLIB components. By virtue of this optical assembly design, when one cylindrical lens array is momentarily stationary during beam direction reversal, the other cylindrical lens array is moving in an independent manner, thereby causing the transmitted PLIB 307 to be spatial phase modulated even at times when one cylindrical lens array is reversing its direction (i.e. momentarily at rest). In an alternative embodiment, one of the cylindrical lens arrays can be mounted stationary relative to the PLIA, while the other cylindrical lens array is micro-oscillated relative to the stationary cylindrical lens array

In the illustrative embodiment, each cylindrical lens array 301A and 301B is realized as a lenticular screen having 64 cylindrical lenslets per inch. For a speckle-noise power reduction of five (5x), it was determined experimentally that about 25 or more substantially different speckle-noise patterns must be generated during a photo-integration time period of $1/10000^{th}$ second, and that a 125 micron shift (Δx) in the cylindrical lens arrays was required, thereby requiring an array velocity of about 1.25 meters/second. Using a sinusoidal function to drive each cylindrical lens array, the array velocity is described by the equation $V=A\omega\sin(\omega t)$, where $A=3\times10^{-3}$ meters and $\omega=370$ radians/second (i.e. 60Hz) providing about a peak array velocity of about 1.1 meter/second. Notably, one can increase the number of substantially different speckle-noise patterns produced during the photo-integration time period of the image detection array by either (i) increasing the spatial period of each cylindrical lens array, and/or (ii) increasing the relative velocity cylindrical lens array(s) and the PLIB transmitted therethrough during object illumination operations. Increasing either of this parameters will have the effect of increasing the spatial gradient of the spatial phase modulation function (SPMF) of the optical assembly, causing steeper transitions in phase delay along the wavefront of the PLIB, as the cylindrical lens arrays move relative to the PLIB being transmitted therethrough. Expectedly, this will generate more components with greater magnitude values on the spatial-frequency domain of the system, thereby producing more independent virtual spatially-incoherent illumination sources in the system. This will tend to reduce the RMS power of speckle-noise patterns observed at the image detection array.

<u>Conditions For Producing Uncorrelated Time-Varying Speckle-Noise Pattern Variations At The Image Detection Array of The IFD Module (i.e. Camera Subsystem)</u>

In general, each method of speckle-noise reduction according to the present invention requires modulating the either the phase, intensity, or frequency of the transmitted PLIB (or

reflected/received PLIB) so that numerous substantially different time-varying speckle-noise patterns are generated at the image detection array each photo-integration time period/interval thereof. By achieving this general condition, the planar laser illumination beam (PLIB), either transmitted to the target object, or reflected therefrom and received by the IFD subsystem, is rendered partially coherent or coherent-reduced in the spatial and/or temporal sense. This ensures that the speckle-noise patterns produced at the image detection array are statistically uncorrelated, and therefore can be temporally and possibly spatially averaged at each image detection element during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-patterns observed at the image detection array. The amount of RMS power reduction that is achievable at the image detection array is, therefore, dependent upon the number of substantially different time-varying speckle-noise patterns that are generated at the image detection array during its photo-integration time period thereof. For any particular speckle-noise reduction apparatus of the present invention, a number parameters will factor into determining the number of substantially different time-varying speckle-noise patterns that must be generated each photo-integration time period, in order to achieve a particular degree of reduction in the RMS power of speckle-noise patterns at the image detection array.

Referring to Fig. 1I3E, a geometrical model of a subsection of the optical assembly of Fig. 1I3A is shown. This simplified model illustrates the first order parameters involved in the PLIB spatial phase modulation process, and also the relationship among such parameters which ensures that at least one cycle of speckle-noise pattern variation will be produced at the image detection array of the IFD module (i.e. camera subsystem). As shown, this simplified model is derived by taking a simple case example, where only two virtual laser illumination sources (such as those generated by two cylindrical lenslets) are illuminating a target object. In practice, there will be numerous virtual laser beam sources by virtue of the fact that the cylindrical lens array has numerous lenslets (e.g. 64 lenslets/inch) and cylindrical lens array is micro-oscillated at a particular velocity with respect to the PLIB as the PLIB is being transmitted therethrough.

In the simplified case shown in Fig. 1I3E, wherein spatial phase modulation techniques are employed, the speckle-noise pattern viewed by the pair of cylindrical lens elements of the imaging array will become uncorrelated with respect to the original speckle-noise pattern (produced by the real laser illumination source) when the difference in phase among the wavefronts of the individual beam components is on the order of 1/2 of the laser illumination wavelength λ. For the case of a moving cylindrical lens array, as shown in Fig. 1I3A, this decorrelation condition occurs when:

$$\Delta x > \lambda D / 2 P$$

wherein, Δx is the motion of the cylindrical lens array, λ is the characteristic wavelength of the laser illumination source, D is the distance from the laser diode (i.e. source) to the cylindrical lens array, and P is the separation of the lenslets within the cylindrical lens array. This condition ensures that one cycle of speckle-noise pattern variation will occur at the image detection array of the IFD Subsystem for each movement of the cylindrical lens array by distance Δx. This implies that, for the apparatus of Fig. 1I3A, the time-varying speckle-noise patterns detected by the image detection array of IFD subsystem will become statistically uncorrelated or independent (i.e. substantially different) with respect to the original speckle-noise pattern produced by the real laser illumination sources, when the spatial gradient in the phase of the beam wavefront is greater than or equal to $\lambda/2P$.

<u>Conditions For Temporally Averaging Time-Varying Speckle-Noise Patterns At The Image Detection Array of The IFD Subsystem In Accordance With The Principles Of The Present Invention</u>

To ensure additive cancellation of the uncorrelated time-varying speckle-noise patterns detected at the (coherent) image detection array, it is necessary that numerous substantially different (i.e. uncorrelated) time-varying speckle-noise patterns are generated during each the photo-integration time period. In the case of optical system of Fig. 1I3A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of each refractive cylindrical lens array; (ii) the width dimension of each cylindrical lenslet; (iii) the length of each lens array; (iv) the velocity thereof; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of the system. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I3A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, it should be noted that

this minimum sampling parameter threshold is expressed on the time domain, and that expectedly, the lower threshold for this sample number at the image detection (i.e. observation) end of the PLIIM-based system, for a particular degree of speckle-noise power reduction, can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

By ensuring that these two conditions are satisfied to the best degree possible (at the planar laser illumination subsystem and the camera subsystem) will ensure optimal reduction in speckle-noise patterns observed at the image detector of the PLIIM-based system of the present invention. In general, the reduction in the RMS power of observable speckle-noise patterns will be proportional to the square root of the number of statistically uncorrelated real and virtual illumination sources created by the speckle-noise reduction technique of the present invention. Figs. 1I3F and 1I3G illustrate that significant mitigation in speckle-noise patterns can be achieved when using the particular apparatus of Fig. 1I3A in accordance with the first generalized speckle-noise pattern reduction method illustrated in Figs. 1I1 through 1I2B.

Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Light Diffractive (e.g. Holographic) Cylindrical Lens Arrays To Spatial Phase Modulate The Planar Laser Illumination Beam Prior To Target Object Illumination

In Fig. 1I4A, there is shown an optical assembly 310 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 310 comprises a PLIA 6A, 6B with a pair of (holographically-fabricated) diffractive-type cylindrical lens arrays 311A and 311B, and an electronically-controlled PLIB micro-oscillation mechanism 312 for micro-oscillating the cylindrical lens arrays 311A and 311B along the planar extent of the PLIB. In accordance with the first generalized method, the pair of cylindrical lens arrays 311A and 311B are micro-oscillated, relative to each other (out of phase by 90 degrees) using two pairs of ultrasonic transducers 313A, 313B and 314A, 314B arranged in a push-pull configuration. The individual beam components within the transmitted PLIB 315 are micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity v(t) which causes the spatial phase along the wavefront of the transmitted PLIB to be spatially modulated, causing numerous substantially different (i.e. uncorrelated) time-varying speckle-noise patterns to be generated at the image detection array of the IFD Subsystem during the photo-integration time period thereof. The numerous time-varying speckle-noise patterns produced at the image detection array are temporally (and possibly spatially) averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I4C, an array support frame 316 with a light transmission window 317 and recesses 318A and 318B is used to mount the pair of cylindrical lens arrays 311A and 311B in a relative reciprocating manner, and thus permitting micro-oscillation in accordance with the principles of the present invention. In 1I4D, the pair of cylindrical lens arrays 311A and 311B are shown configured between a pair of ultrasonic transducers 313A, 313B and 314A, 314B (or flexural elements driven by voice-coil type devices) mounted in recesses 318A and 318B, respectively, and operated in a push-pull mode of operation. By employing dual cylindrical lens arrays in this optically assembly, the transmitted PLIB 315 is spatial phase modulated in a continual manner during object illumination operations. By virtue of this optical assembly design, when one cylindrical lens array is momentarily stationary during beam direction reversal, the other cylindrical lens array is moving in an independent manner, thereby causing the transmitted PLIB to be spatial phase modulated even when the cylindrical lens array is reversing its direction.

In the case of optical system of Fig. 1I4A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of (each) HOE cylindrical lens array; (ii) the width dimension of each HOE; (iii) the length of each HOE lens array; (iv) the velocity thereof; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for time averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at detection array can hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I4A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Reflective Elements Relative To A Stationary Refractive Cylindrical Lens Array To Spatial Phase Modulate A Planar Laser Illumination Beam Prior To Target Object Illumination

In Fig. 1I5A, there is shown an optical assembly 320 for use in any PLIIM-based system of the present invention. As shown, the optical assembly comprises a PLIA 6A, 6B with a stationary (refractive-type or diffractive-type) cylindrical lens array 321, and an electronically-controlled micro-oscillation mechanism 322 for micro-oscillating a pair of reflective-elements 324A and 324B along the planar extent of the PLIB, relative to a stationary refractive-type cylindrical lens array 321 and a stationary reflective element (i.e. mirror element) 323. In accordance with the first generalized method, the pair of reflective elements 324A and 324B are micro-oscillated relative to each other (at 90 degrees out of phase) using two pairs of ultrasonic transducers 325A, 325B and 326A, 326B arranged in a push-pull configuration. The transmitted PLIB is micro-oscillated (i.e. move) along the planar extent thereof (i) by an amount of distance Δx or greater at a velocity v(t) which causes the spatial phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns generated at the image detection array of the IFD Subsystem during the photo-integration time period thereof. The numerous time-varying speckle-noise patterns are temporally and possibly spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I5B, a planar mirror 323 reflects the PLIB components towards a pair of reflective elements 324A and 324B which are pivotally connected to a common point 327 on support post 328. These reflective elements 324A and 324B are reciprocated and micro-oscillate the incident PLIB components along the planar extent thereof in accordance with the principles of the present invention. These micro-oscillated PLIB components are transmitted through a cylindrical lens array so that they are optically combined and numerous phase-delayed PLIB components are projected onto the same points on the surface of the object being illuminated. As shown in Fig. 1I5D, the pair of reflective elements 324A and 324B are configured between two pairs of ultrasonic transducers 325A, 325B and 326A, 326B (or flexural elements driven by voice-coil type devices) supported on posts 330A, 330B operated in a push-pull mode of operation. By employing dual reflective elements in this optical assembly, the transmitted PLIB 331 is spatial phase modulated in a continual manner during object illumination operations. By virtue of this optical assembly design, when one reflective element is momentarily stationary while reversing its direction, the other reflective element is moving in an independent manner, thereby causing the transmitted PLIB 331 to be continually spatial phase modulated.

In the case of optical system of Fig. 1I5A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array; (ii) the width dimension of each cylindrical lenslet; (iii) the length of each HOE lens array; (iv) the length and angular velocity of the reflector elements; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I5A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination Beam (PLIB) Using An Acoustic-Optic Modulator To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I6A, there is shown an optical assembly 340 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 340 comprises a PLIA 6A, 6B with a cylindrical lens array 341, and an acousto-optical (i.e. Bragg Cell) beam deflection mechanism 343 for micro-oscillating the PLIB 343 prior to illuminating the target object. In accordance with the first generalized method, the PLIB 344 is micro-oscillated by an acousto-optical (i.e. Bragg Cell) beam deflection device 345 as acoustical waves (signals) 346 propagate through the electro-acoustical device transverse to the direction of transmission of the PLIB 344. This causes the beam components of the composite PLIB 344 to be micro-oscillated (i.e. moved) the along the planar extent thereof by an amount of distance Δx or greater at a velocity $v(t)$. Such a micro-oscillation movement causes the spatial phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns

generated at the image detection array during the photo-integration time period thereof. The numerous time-varying speckle-noise patterns are temporally and possibly spatially averaged at the image detection array during each the photo-integration time period thereof. As shown, the acousto-optical beam deflective panel 345 is driven by control signals supplied by electrical circuitry under the control of camera control computer 22.

In the illustrative embodiment, beam deflection panel 345 is made from an ultrasonic cell comprising: a pair of spaced-apart optically transparent panels 346A and 346B, containing an optically transparent, ultrasonic-wave carrying fluid, e.g. toluene (i.e. CH_3 C_6 H_5) 348; a pair of end panels 348A and 348B cemented to the side and end panels to contain the ultrasonic wave carrying fluid 348 within the cell structure formed thereby; an array of piezoelectric transducers 349 mounted through end wall 349A; and an ultrasonic-wave dampening material 350 disposed at the opposing end wall panel 349B, on the inside of the cell, to avoid reflections of the ultrasonic wave at the end of the cell. Electronic drive circuitry is provided for generating electrical drive signals for the acoustical wave cell 345 under the control of the camera control computer 22. In the illustrative embodiment, these electrical drives signals are provided to the piezoelectric transducers 349 and result in the generation of an ultrasonic wave that propagates at a phase velocity through the cell structure, from one end to the other. This causes a modulation of the refractive index of the ultrasonic wave carrying fluid 348, and thus a modulation of the spatial phase along the wavefront of the transmitted PLIB, thereby causing the same to be periodically swept across the cylindrical lens array 341. The micro-oscillated PLIB components are optically combined as they are transmitted through the cylindrical lens array 341 and numerous phase-delayed PLIB components are projected onto the same points of the surface of the object being illuminated. After reflecting from the object and being modulated by the micro-structure thereof, the received PLIB produces numerous substantially different time-varying speckle-noise patterns on the image detection array of the PLIIM-based system during the photo-integration time period thereof. These time-varying speckle-noise patterns are temporally and spatially averaged at the image detection array, thereby reducing the power of speckle-noise patterns observable at the image detection array.

In the case of optical system of Fig. 1I6A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial frequency of the cylindrical lens array; (ii) the width dimension of each lenslet; (iii) the temporal and velocity characteristics of the acoustical wave 348 propagating through the acousto-optical cell structure 345; (iv) the optical density characteristics of the ultrasonic wave carrying fluid 348; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the

spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof.

One can expect an increase the number of substantially different speckle-noise patterns produced during the photo-integration time period of the image detection array by either: (i) increasing the spatial period of each cylindrical lens array; (ii) the temporal period and rate of repetition of the acoustical waveform propagating along the cell structure 345; and/or (iii) increasing the relative velocity between the stationary cylindrical lens array and the PLIB transmitted therethrough during object illumination operations, by increasing the velocity of the acoustical wave propagating through the acousto-optical cell 345. Increasing either of these parameters should have the effect of increasing the spatial gradient of the spatial phase modulation function (SPMF) of the optical assembly, e.g. by causing steeper transitions in phase delay along the wavefront of the composite PLIB, as it is transmitted through cylindrical lens array 341 in response to the propagation of the acoustical wave along the cell structure 345. Expectedly, this should generate more components with greater magnitude values on the spatial-frequency domain of the system, thereby producing more independent virtual spatially-incoherent illumination sources in the system. This should tend to reduce the RMS power of speckle-noise patterns observed at the image detection array.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I6A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this "sample number" at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB and/or the time derivative of the phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination Beam (PLIB) Using A Piezo-Electric Driven Deformable Mirror Structure To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I7A, there is shown an optical assembly 360 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 360 comprises a PLIA 6A, 6B with a cylindrical lens array 361 (supported within a frame 362), and an electro-mechanical PLIB micro-oscillation mechanism 363 for micro-oscillating the PLIB prior to transmission to the

target object to be illuminated. In accordance with the first generalize method, the PLIB components produced by PLIA 6A, 6B are reflected off a piezo-electrically driven deformable mirror (DM) structure 364 arranged in front of the PLIA, while being micro-oscillated along the planar extent of the PLIBs. These micro-oscillated PLIB components are reflected back towards a stationary beam folding mirror 365 mounted (above the optical path of the PLIB components) by support posts 366A, 366B and 366C, reflected thereoff and transmitted through cylindrical lens array 361 (e.g. operating according to refractive, diffractive and/or reflective principles). These micro-oscillated PLIB components are optically combined by the cylindrical lens array so that numerous phase-delayed PLIB components are projected onto the same points on the surface of the object being illuminated. During PLIB transmission, in the case of an illustrative embodiment involving a high-speed tunnel scanning system, the surface of the DM structure 364 (Δx) is periodically deformed at frequencies in the 100kHz range and at few microns amplitude, to produce moving ripples aligned along the direction that is perpendicular to planar extent of the PLIB (i.e. along its beam spread). These moving ripples cause the beam components within the PLIB 367 to be micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity v(t) which modules the spatial phase among the wavefront of the transmitted PLIB and produces numerous substantially different time-varying speckle-noise patterns at the image detection array during the photo-integration time period thereof. These numerous substantially different time-varying speckle-noise patterns are temporally and possibly spatially averaged during each photo-integration time period of the image detection array. Fig. 1I7A shows the optical path which the PLIB travels while undergoing spatial phase modulation by the piezo-electrically driven DM structure 364 during target object illumination operations.

In the case of optical system of Fig. 1I7A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array; (ii) the width dimension of each lenslet; (iii) the temporal and velocity characteristics of the surface deformations produced along the DM structure 364; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design.

In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Notably, one can expect an increase the number of substantially different speckle-noise patterns

produced during the photo-integration time period of the image detection array by either: (i) increasing the spatial period of each cylindrical lens array; (ii) the spatial gradient of the surface deformations produced along the DM structure 364; and/or (iii) increasing the relative velocity between the stationary cylindrical lens array and the PLIB transmitted therethrough during object illumination operations, by increasing the velocity of the surface deformations along the DM structure 364. Increasing either of these parameters should have the effect of increasing the spatial gradient of the spatial phase modulation function (SPMF) of the optical assembly, causing steeper transitions in phase delay along the wavefront of the composite PLIB, as it is transmitted through cylindrical lens array in response to the propagation of the acoustical wave along the cell. Expectedly, this should generate more components with greater magnitude values on the spatial-frequency domain of the system, thereby producing more independent virtual spatially-incoherent illumination sources in the system. This should tend to reduce the RMS power of speckle-noise patterns observed at the image detection array.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I7A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this "sample number" at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB and/or the time derivative of the phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination Beam (PLIB) Using A Refractive-Type Phase-Modulation Disc To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination

In Fig. 1I8A, there is shown an optical assembly 370 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 370 comprises a PLIA 6A, 6B with cylindrical lens array 371, and an optically-based PLIB micro-oscillation mechanism 372 for micro-oscillating the PLIB 373 transmitted towards the target object prior to illumination. In accordance with the first generalize method, the PLIB micro-oscillation mechanism 372 is realized by a refractive-type phase-modulation disc 374, rotated by an electric motor 375 under the control of the camera control computer 22. As shown in Figs. 1I8B and 1I8D, the PLIB form PLIA 6A is transmitted perpendicularly through a sector of the phase modulation disc 374, as shown in Fig. 1I8D. As shown in Fig. 1I8D, the disc comprises numerous sections 376, each having refractive indices that vary sinusoidally at different angular positions along the disc.

Preferably, the light transmittivity of each sector is substantially the same, as only spatial phase modulation is the desired light control function to be performed by this subsystem. Also, to ensure that the spatial phase along the wavefront of the PLIB is modulated along its planar extent, each PLIA 6A, 6B should be mounted relative to the phase modulation disc so that the sectors 376 move perpendicular to the plane of the PLIB during disc rotation. As shown in Fig. 1I8D, this condition can be best achieved by mounting each PLIA 6A, 6B as close to the outer edge of its phase modulation disc as possible where each phase modulating sector moves substantially perpendicularly to the plane of the PLIB as the disc rotates about its axis of rotation.

During system operation, the refractive-type phase-modulation disc 374 is rotated about its axis through the composite PLIB 373 so as to modulate the spatial phase along the wavefront of the PLIB and produce numerous substantially different time-varying speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and possibly spatially averaged during each photo-integration time period of the image detection array. As shown in Fig. 1I8E, the electric field components produced from the rotating refractive disc sections 371 and its neighboring cylindrical lenslet 371 are optically combined by the cylindrical lens array and projected onto the same points on the surface of the object being illuminated, thereby contributing to the resultant time-varying (uncorrelated) electric field intensity produced at each detector element in the image detection array of the IFD Subsystem.

In the case of optical system of Fig. 1I8A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array; (ii) the width dimension of each lenslet; (iii) the length of the lens array in relation to the radius of the phase modulation disc 374; (iv) the tangential velocity of the phase modulation elements passing through the PLIB; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I8A, the number of substantially different time-varying speckle-noise pattern samples which need to be

generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination Beam (PLIB) Using A Phase-Only Type LCD-Based Phase Modulation Panel To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination

As shown in Figs. 1I8F and 1I8G, the general phase modulation principles embodied in the apparatus of Fig. 1I8A can be applied in the design the optical assembly for reducing the RMS power of speckle-noise patterns observed at the image detection array of a PLIIM-based system. As shown in Figs. 1I8F and 1I8G, optical assembly 700 comprises: a backlit transmissive-type phase-only LCD (PO-LCD) phase modulation panel 701 mounted slightly beyond a PLIA 6A, 6B to intersect the composite PLIB 702; and a cylindrical lens array 703 supported in frame 704 and mounted closely to, or against phase modulation panel 701. The phase modulation panel 701 comprises an array of vertically arranged phase modulating elements or strips 705, each made from birefrigent liquid crystal material. In the illustrative embodiment, phase modulation panel 701 is constructed from a conventional backlit transmission-type LCD panel. Under the control of camera control computer 22, programmed drive voltage circuitry 706 supplies a set of phase control voltages to the array 705 so as to controllably vary the drive voltage applied across the pixels associated with each predefined phase modulating element 705. Each phase modulating element 705 is assigned a particular phase coding so that periodic or random micro-shifting of PLIB 708 is achieved along its planar extent prior to transmission through cylindrical lens array 703. During system operation, the phase-modulation panel 701 is driven by applying control voltages across each element 705 so as to modulate the spatial phase along the wavefront of the PLIB, to cause each PLIB component to micro-oscillate as it is transmitted therethrough. These micro-oscillated PLIB components are then transmitted through cylindrical lens array so that they are optically combined and numerous phase-delayed PLIB components are projected 703 onto the same points of the surface of the object being illuminated. This illumination process results in producing numerous substantially different time-varying speckle-noise patterns at the image detection array (of the accompanying IFD subsystem) during the photo-integration time period thereof. These time-varying speckle-noise patterns are temporally and possibly spatially

averaged thereover, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I8F, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array 703; (ii) the width dimension of each lenslet thereof; (iii) the length of the lens array in relation to the radius of the phase modulation panel 701; (iv) the speed at which the birefringence of each modulation element 705 is electrically switched during the photo-integration time period of the image detection array; and (v) the number of real laser illumination sources employed in each planar laser illumination array (PLIA) in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I8F, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination Beam (PLIB) Using A Refractive-Type Cylindrical Lens Array Ring Structure To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination

In Fig. 1I9A, there is shown a pair of optical assemblies 380A and 380B for use in any PLIIM-based system of the present invention. As shown, each optical assembly 380 comprises a PLIA 6A, 6B with a PLIB phase-modulation mechanism 381 realized by a refractive-type cylindrical lens array ring structure 382 for micro-oscillating the PLIB prior to illuminating the target object. The lens array ring structure 382 can be made from a lenticular screen material having cylindrical lens elements (CLEs) or cylindrical lenslets arranged with a high spatial period (e.g. 64 CLEs per inch). The lenticular screen material can be carefully heated to soften

the material so that it may be configured into a ring geometry, and securely held at its bottom end within a groove formed within support ring 382, as shown in Fig. 1I9B. In accordance with the first generalized method, the refractive-type cylindrical lens array ring structure 382 is rotated by a high-speed electric motor 384 about its axis through the PLIB 383 produced by the PLIA 6A, 6B. The function of the rotating cylindrical lens array ring structure 382 is to module the phase along the wavefront of the PLIB, producing numerous phase-delayed PLIB components which are optically combined, which are projected onto the same points of the surface of the object being illuminated. This illumination process produces numerous substantially different time-varying speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array.

As shown in Fig. 1I9B, the cylindrical lens ring structure 382 comprises a cylindrically-configured array of cylindrical lens 386 mounted perpendicular to the surface of an annulus structure 387, connected to the shaft of electric motor 384 by way of support arms 388A, 388B, 388C and 388D. The cylindrical lenslets should face radially outwardly, as shown in Fig. 1I9B. As shown in Fig. 1I9A, the PLIA 6A, 6B is stationarily mounted relative to the rotor of the motor 384 so that the PLIB 383 produced therefrom is oriented substantially perpendicular to the axis of rotation of the motor, and is transmitted through each cylindrical lens element 386 in the ring structure 382 at an angle which is substantially perpendicular to the longitudinal axis of each cylindrical lens element 386. The composite PLIB 389 produced from optical assemblies 380A and 380B is spatially coherent-reduced and yields images having reduced speckle-noise patterns in accordance with the present invention.

In the case of the optical system of Fig. 1I9A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens elements in the lens array ring structure; (ii) the width dimension of each cylindrical lens element; (iii) the circumference of the cylindrical lens array ring structure; (iv) the tangential velocity thereof at the point where the PLIB intersects the transmitted PLIB; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period

thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I9A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination Beam (PLIB) Using A Diffractive-Type Cylindrical Lens Array Ring Structure To Spatial Intensity Modulate Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I10A, there is shown a pair of optical assemblies 390A and 390B for use in any PLIIM-based system of the present invention. As shown, each optical assembly 390 comprises a PLIA 6A, 6B with a PLIB phase-modulation mechanism 391 realized by a diffractive (i.e. holographic) type cylindrical lens array ring structure 392 for micro-oscillating the PLIB 393 prior to illuminating the target object. The lens array ring structure 392 can be made from a strip of holographic recording material 392A which has cylindrical lenses elements holographically recorded therein using conventional holographic recording techniques. This holographically recorded strip 392A is sandwiched between an inner and outer set of glass cylinders 392B and 392C, and sealed off from air or moisture on its top and bottom edges using a glass sealant. The holographically recorded cylindrical lens elements (CLEs) are arranged about the ring structure with a high spatial period (e.g. 64 CLEs per inch). HDE construction techniques disclosed in copending U.S. Application No. 09/071,512, incorporated herein by reference, can be used to manufacture the HDE ring structure 312. The ring structure 392 is securely held at its bottom end within a groove formed within annulus support structure 397, as shown in Fig. 1I10B. As shown therein, the cylindrical lens ring structure 392 is mounted perpendicular to the surface of an annulus structure 397, connected to the shaft of electric motor 394 by way of support arms 398A, 398B, 398C, and 398D. As shown in Fig. 1I10A, the PLIA 6A, 6B is stationarily mounted relative to the rotor of the motor 394 so that the PLIB 393 produced therefrom is oriented substantially perpendicular to the axis of rotation of the motor 394, and is transmitted through each holographically-recorded cylindrical lens element (HDE) 396 in the ring structure 392 at an angle which is substantially perpendicular to the longitudinal axis of each cylindrical lens element 396.

In accordance with the first generalized method, the cylindrical lens array ring structure 392 is rotated by a high-speed electric motor 394 about its axis as the composite PLIB is transmitted from the PLIA 6A through the rotating cylindrical lens array ring structure. During the transmission process, the phase along the wavefront of the PLIB is spatial phase modulated. The function of the rotating cylindrical lens array ring structure 392 is to module the phase along the wavefront of the PLIB producing spatial phase modulated PLIB components which are optically combined and projected onto the same points of the surface of the object being illuminated. This illumination process produces numerous substantially different time-varying speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof. These time-varying speckle-noise patterns are temporally and spatially averaged at the image detector during each photo-integration time, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I10A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens elements in the lens array ring structure; (ii) the width dimension of each cylindrical lens element; (iii) the circumference of the cylindrical lens array ring structure; (iv) the tangential velocity thereof at the point where the PLIB intersects the transmitted PLIB; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I9A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination Beam (PLIB) Using A Reflective-Type Phase Modulation Disc Structure To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination</u>

In Figs. 1I11A through 1I11C, there is shown a PLIIM-based system 400 embodying a pair of optical assemblies 401A and 401B, each comprising a reflective-type phase-modulation mechanism 402 mounted between a pair of PLIAs 6A1 and 6A2, and towards which the PLIAs 6B1 and 6B2 direct a pair of composite PLIBs 402A and 402B. In accordance with the first generalized method, the phase-modulation mechanism 402 comprises a reflective-type PLIB phase-modulation disc structure 404 having a cylindrical surface 405 with randomly or periodically distributed relief (or recessed) surface discontinuities that function as "spatial phase modulation elements". The phase modulation disc 404 is rotated by a high-speed electric motor 407 about its axis so that, prior to illumination of the target object, each PLIB 402A and 402B is reflected off the phase modulation surface of the disc 404 as a composite PLIB 409 (i.e. in a direction of coplanar alignment with the field of view (FOV) of the IFD subsystem), spatial phase modulates the PLIB and causing the PLIB 409 to be micro-oscillated along its planar extent. **The function of each rotating phase-modulation disc 404 is to module the phase along** the wavefront of the PLIB, producing numerous phase-delayed PLIB components which are optically combined and projected onto the same points of the surface of the object being illuminated. This produces numerous substantially different time-varying speckle-noise patterns at the image detection array during each photo-integration time period (i.e. interval) thereof. The time-varying speckle-noise patterns are temporally and spatially averaged at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observe at the image detection array. As shown in Fig. 1I11B, the reflective phase-modulation disc 404, while spatially-modulating the PLIB, does not effect the coplanar relationship maintained between the transmitted PLIB 409 and the field of view (FOV) of the IFD Subsystem.

In the case of optical system of Fig. 1I11A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the spatial phase modulating elements arranged on the surface 405 of each disc structure 404; (ii) the width dimension of each spatial phase modulating element on surface 405; (iii) the circumference of the disc structure 404; (iv) the tangential velocity on surface 405 at which the PLIB reflects thereoff; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in

reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I11A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Producing A Micro-Oscillating Planar Laser Illumination (PLIB) Using A Rotating Polygon Lens Structure Which Spatial Phase Modulates Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I12A, there is shown an optical assembly 417 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 417 comprises a PLIA 6A′, 6B′ and stationary cylindrical lens array 341 maintained within frame 342, wherein each planar laser illumination module (PLIM) 11′ employed therein includes an integrated phase-modulation mechanism. In accordance with the first generalized method, the PLIB micro-oscillation mechanism is realized by a multi-faceted (refractive-type) polygon lens structure 16′ having an array of cylindrical lens surfaces 16A′ symmetrically arranged about its circumference. As shown in Fig. 1I12C, each cylindrical lens surface 16A′ is diametrically opposed from another cylindrical lens surface arranged about the polygon lens structure so that as a focused laser beam is provided as input on one cylindrical lens surface, a planarized laser beam exits another (different) cylindrical lens surface diametrically opposed to the input cylindrical lens surface.

As shown in Fig. 1I12B, the multi-faceted polygon lens structure 16′ employed in each PLIM 11′ is rotatably supported within housing 418A (comprising housing halves 418A1 and 418A2). A pair of sealed upper and lower ball bearing sets 418B1 and 418B2 are mounted within the upper and lower end portions of the polygon lens structure 16′ and slidably secured within upper and lower raceways 418C1 and 418C2 formed in housing halves 418A1 and 418A2, respectively. As shown, housing half 418A1 has an input light transmission aperture 418D1 for passage of the focused laser beam from the VLD, whereas housing half 418A2 has an elongated output light transmission aperture 418D2 for passage of a component PLIB. As

shown, the polygon lens structure 16′ is rotatably supported within the housing when housing halves 418A1 and 418A2 are brought physically together and interconnected by screws, ultrasonic welding, or other suitable fastening techniques.

As shown in Fig. 1I12C, a gear element 418E is fixed attached to the upper portion of each polygon lens structure 16′ in the PLIA. Also, as shown in Fig. 1I12D, each neighboring gear element is intermeshed and one of these gear elements is directly driven by an electric motor 418H so that the plurality of polygon lens structures 16′ are simultaneously rotated and a plurality of component PLIBs 419A are generated from their respective PLIMs during operation of the speckle-pattern noise reduction assembly 417, and a composite PLIB 418B is produced from cylindrical lens array 341.

In accordance with the first generalized method of speckle-pattern noise reduction, each polygon lens structure is rotated about its axis during system operation. During system operation, each polygon lens structure 16′ is rotated about its axis, and the composite PLIB transmitted from the PLIA 6A′, 6B′ is spatial phase modulated along the planar extent thereof, producing numerous phase-delayed PLIB components. The function of the cylindrical lens array 341 is to optically combine these numerous phase-delayed PLIB components and project the same onto the points of the object being illuminated. This causes the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof. The numerous time-varying speckle-noise patterns produced at the image detection array are temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I12A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens surfaces; (ii) the width dimension of each cylindrical lens surface; (iii) the circumference of the polygon lens structure; (iv) the tangential velocity of the cylindrical lens surfaces through which focused laser beam are transmitted; and (v) the number of real laser illumination sources employed in each planar laser illumination array (PLIA) in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the

above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I12A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Second Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Temporal Coherence Of The Planar Laser Illumination Beam (PLIB) Before It Illuminates The Target Object By Applying Temporal Intensity Modulation Techniques During The Transmission Of The PLIB Towards The Target</u>

Referring to Figs. 1I13 through 1I15F, the second generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of temporal intensity modulating the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object (e.g. package) therewith so that the object is illuminated with a temporally coherent-reduced planar laser beam and, as a result, numerous substantially different time-varying speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array (in the IFD subsystem). These speckle-noise patterns are temporally averaged and/or spatially averaged and the observable speckle-noise patterns reduced. This method can be practiced with any of the PLIIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I13B, the first step of the second generalized method shown in Figs. 1I13 through 1I13A involves modulating the temporal intensity of the transmitted planar laser illumination beam (PLIB) along the planar extent thereof according to a (random or periodic) temporal-intensity modulation function (TIMF) prior to illumination of the target object with the PLIB. This causes numerous substantially different time-varying speckle-noise patterns to be produced at the image detection array during the photo-integration time period thereof. As indicated at Block B in Fig. 1I13B, the second step of the method involves temporally and spatially averaging the numerous time-varying speckle-noise patterns detected during each photo-integration time period of the image detection array in the IFD

Subsystem, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array.

When using the second generalized method, the target object is repeatedly illuminated with planes of laser light apparently originating at different moments in time (i.e. from different virtual illumination sources) over the photo-integration period of each detector element in the image detection array of the PLIIM-based system. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual illumination sources are effectively rendered temporally incoherent (or temporally coherent-reduced) with respect to each other. On a time-average basis, virtual illumination sources produce these time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of the observed speckle-noise patterns. As speckle-noise patterns are roughly uncorrelated at the image detector, the reduction in speckle noise amplitude should be proportional to the square root of the number of independent real and virtual laser illumination sources contributing to the illumination of the target object and formation of the image frames thereof. As a result of the method of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The second generalized method above can be explained in terms of Fourier Transform optics. When temporally modulating the transmitted PLIB by a periodic or random temporal intensity modulation (TIMF) function, while satisfying conditions (i) and (ii) above, a temporal intensity modulation process occurs on the time domain. This temporal intensity modulation process is equivalent to mathematically multiplying the transmitted PLIB by the temporal intensity modulation function. This multiplication process on the time domain is equivalent on the time-frequency domain to the convolution of the Fourier Transform of the temporal intensity modulation function with the Fourier Transform of the transmitted PLIB. On the time-frequency domain, this convolution process generates temporally-incoherent (i.e. statistically-uncorrelated) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of each detector element, to reduce the RMS power of speckle-noise patterns observed at the image detection array.

In general, various types of temporal intensity modulation techniques can be used to carry out the first generalized method including, for example: mode-locked laser diodes (MLLDs) employed in the planar laser illumination array; electro-optical temporal intensity modulators disposed along the optical path of the composite planar laser illumination beam;

internal and external type laser beam frequency modulation (FM) devices; internal and external laser beam amplitude modulation (AM) devices; etc. Several of these temporal intensity modulation mechanisms will be described in detail below.

Electro-Optical Apparatus Of The Present Invention For Temporal Intensity Modulating The Planar Laser Illumination (PLIB) Beam Prior To Target Object Illumination Employing High-Speed Beam Gating/Shutter Principles

In Figs. 1I14A through 1I14B, there is shown an optical assembly 420 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 420 comprises a PLIA 6A, 6B with a refractive-type cylindrical lens array 421 (e.g. operating according to refractive, diffractive and/or reflective principles) supported in frame 822, and an electrically-active temporal intensity modulation panel 423 (e.g. high-speed electro-optical gating/shutter device) arranged in front of the cylindrical lens array 421. Electronic driver circuitry 424 is provided to drive the temporal intensity modulation panel 43 under the control of camera control computer 22. In the illustrative embodiment, electronic driver circuitry 424 can be programmed to produce an output PLIB 425 consisting of a periodic light pulse train, wherein each light pulse has an ultra-short time duration and a rate of repetition (i.e. temporal characteristics) which generate spectral harmonics (i.e. components) on the time-frequency domain. These spectral harmonics, when optically combined by cylindrical lens array 421, and projected onto a target object, illuminate the same points on the surface thereof, and reflect/scatter therefrom, resulting in the generation of numerous time-varying speckle-patterns at the image detection array during each photo-integration time period thereof in the PLIIM-based system.

During system operation, the PLIB 424 is temporal intensity modulated according to a (random or periodic) temporal-intensity modulation (e.g. windowing) function (TIMF) so that numerous substantially different time-varying speckle-noise patterns are produced at the image detection array during the photo-integration time period thereof. The time-varying speckle-noise patterns detected at the image detection array are temporally and spatially averaged during each photo-integration time period thereof, thus reducing the RMS power of the speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I14A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated during each photo-integration time period: (i) the time duration of each light pulse in the output PLIB 425; (ii) the rate of repetition of the light pulses in the output PLIB; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (i) and (ii) will factor into the specification of the temporal intensity

modulation function (TIMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I14A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the temporal derivative of the temporal intensity modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Electro-Optical Apparatus Of The Present Invention For Temporal Intensity Modulating The Planar Laser Illumination Beam (PLIB) Prior To Target Object Illumination Employing Visible Mode-Locked Laser Diodes (MLLDs)

In Figs. 1I15A through 1I15B, there is shown an optical assembly 440 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 440 comprises a cylindrical lens array 441 (e.g. operating according to refractive, diffractive and/or reflective principles), mounted in front of a PLIA 6A, 6B embodying a plurality of visible mode-locked visible diodes (MLLDs) 13'. In accordance with the second generalized method of the present invention, each visible MLLD 13' is configured and tuned to produce ultra-short pulses of light having a time duration and at occurring at a rate of repetition (i.e. frequency) which causes the transmitted PLIB 443 to be temporal-intensity modulated according to a (random or periodic) temporal intensity modulation function (TIMF) prior to illumination of the target object with the PLIB. This causes numerous substantially different time-varying speckle-noise patterns produced at the image detection array during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during each photo-integration time period of the image detection array in the IFD Subsystem, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I15B, each MLLD 13' employed in the PLIA of Fig. 1I15A comprises: a multi-mode laser diode cavity 444 referred to as the active layer (e.g. InGaAsP) having a wide emission-bandwidth over the visible band, and suitable time-bandwidth product for the application at hand; a collimating lenslet 445 having a very short focal length; an active mode-

locker 446 (e.g. temporal-intensity modulator) operated under switched electronic control of a TIM controller 447; a passive-mode locker (i.e. saturable absorber) 448 for controlling the pulse-width of the output laser beam; and a mirror 449, affixed to the passive-mode locker 447, having 99% reflectivity and 1% transmittivity at the operative wavelength band of the visible MLLD. The multi-mode diode laser diode 13′ generates (within its primary laser cavity) numerous modes of oscillation at different optical wavelengths within the time-bandwidth product of the cavity. The collimating lenslet 445 collimates the divergent laser output from the diode cavity 444, has a very short local length and defines the aperture of the optical system. The collimated output from the lenslet 445 is directed through the active mode locker 446, disposed at a very short distance away (e.g. 1 millimeter). The active mode locker 446 is typically realized as a high-speed temporal intensity modulator which is electronically-switched between optically transmissive and optically opaque states at a switching frequency equal to the frequency (f_{MLB}) of the mode-locked laser beam pulses to be produced at the output of each MLLD. This laser beam pulse frequency f_{MLB} is governed by the following equation: $f_{MLB}= c/ 2L$, where c is the speed of light, and L is the total length of the MLLD, as defined in Fig. 1I15B. The partially transmission mirror 449, disposed a short distance (e.g. 1 millimeter) away from the active mode locker 446, is characterized by a reflectivity of about 99%, and a transmittance of about 1% at the operative wavelength band of the MLLD. The passive mode locker 448, applied to the interior surface of the mirror 449, is a photo-bleachable saturatable material which absorbs photons at the operative wavelength band. When the passive mode blocker 448 is totally absorbed (i.e. saturated), it automatically transmits the absorbed photons as a burst (i.e. pulse) of output laser light from the visible MLLD. After the burst of photons are emitted, the passive mode blocker 448 quickly recovers for the next photon absorption/saturation/release cycle. Notably, absorption and recovery time characteristics of the passive mode blocker 448 controls the time duration (i.e. width) of the optical pulses produced from the visible MLLD. In typical high-speed package scanning applications requiring a relatively short photo-integration time period (e.g. 10^{-4} sec), the absorption and recovery time characteristics of the passive mode blocker 448 can be on the order of femtoseconds. This will ensure that the composite PLIB 443 produced from the MLLD-based PLIA contains higher order spectral harmonics (i.e. components) with sufficient magnitude to cause a significant reduction in the temporal coherence of the PLIB and thus in the power-density spectrum of the speckle-noise pattern observed at the image detection array of the IFD Subsystem. For further details regarding the construction of MLLDs, reference should be made to "Diode Laser Arrays" (1994), by D. Botez and D.R. Scifres, supra, incorporated herein by reference.

In the case of optical system of Fig. 1I15A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated during each

photo-integration time period: (i) the time duration of each light pulse in the output PLIB 443; (ii) the rate of repetition of the light pulses in the output PLIB; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (i) and (ii) will factor into the specification of the temporal intensity modulation function (TIMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I15C, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the temporal derivative of the temporal intensity modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Electro-Optical Apparatus Of The Present Invention For Temporal Intensity Modulating The Planar Laser Illumination Beam (PLIB) Prior To Target Object Illumination Employing Current-Modulated Visible Laser Diodes (VLDs)

There are other techniques for reducing speckle-noise patterns by temporal intensity modulating PLIBs produced by PLIAs according to the principles of the present invention. A straightforward approach to temporal intensity modulating the PLIB would be to either (i) modulate the diode current driving the VLDs of the PLIA in a non-linear mode of operation, or (ii) use an external optical modulator to temporal intensity modulate the PLIB in a non-linear mode of operation. By operating VLDs in a non-linear manner, high order spectral harmonics can be produced which, in cooperation with a cylindrical lens array, cooperate to generate substantially different time-varying speckle-noise patterns during each photo-integration time period of the image detection array of the PLIIM-based system.

In principal, non-linear amplitude modulation (AM) techniques can be employed with the first approach (i) above, whereas the non-linear AM, frequency modulation (FM), or temporal phase modulation (PM) techniques can be employed with the second approach (ii) above. The primary purpose of applying such non-linear laser modulation techniques is to introduce spectral side-bands into the optical spectrum of the planar laser illumination beam

(PLIB). The spectral harmonics in this side-band spectra are determined by the sum and difference frequencies of the optical carrier frequency and the modulation frequency(ies) employed. If the PLIB is temporal intensity modulated by a periodic temporal intensity modulation (time-windowing) function (e.g. 100% AM), and the time period of this time windowing function is sufficiently high, then two points on the target surface will be illuminated by light of different optical frequencies (i.e. uncorrelated virtual laser illumination sources) carried within pulsed-periodic PLIB. In general, if the difference in optical frequencies in the pulsed-periodic PLIB is large (i.e. caused by compressing the time duration of its constituent light pulses) compared to the inverse of the photo-integration time period of the image detection array, then observed the speckle-noise pattern will appear to be washed out (i.e. additively cancelled) by the beating of the two optical frequencies at the image detection array. To ensure that the uncorrelated speckle-noise patterns detected at the image detection array can additively average (i.e. cancel) out during the photo-integration time period of the image detection array, the rate of light pulse repetition in the transmitted PLIB should be increased to the point where numerous time-varying speckle-patterns are produced thereat, while the time duration (i.e. duty cyce) of each light pulse in the pulsed PLIB is compressed so as to impart greater magnitude to the higher order spectral harmonics comprising the periodic-pulsed PLIB generated by the application of such non-linear modulation techniques.

In Fig. 1I15C, there is shown an optical subsystem 760 for despeckling which comprises a plurality of visible laser diodes (VLDs) 13 and a plurality of cylindrical lens elements 16 arranged in front of a cylindrical lens array 441 supported within a frame 442. Each VLD is driven by a digitally-controlled temporal intensity modulation (TIM) controller 761 so that the PLIB transmitted from the PLIA is temporal intensity modulated according to a temporal-intensity modulation function (TIMF) that is controlled by the programmable drive-current source. This temporal intensity modulation of the transmitted PLIB modulates the temporal phase along the wavefront of the transmitted PLIB, producing numerous substantially different speckle-noise patterns at the image detection array of the IFD subsystem during the photo-integration time period thereof. In turn, these time-varying speckle-patterns are temporally and spatially averaged during the photo-integration time period of the image detection array, thus reducing the RMS power of speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I15D, the temporal intensity modulation (TIM) controller 751 employed in optical subsystem 760 in Fig. 1I15E, comprises: a programmable current source for driving each VLD, which is realized by a voltage source 762, and a digitally-controllable potentiometer 763 configured in series with each VLD 13 in the PLIA; and a programmable microcontroller 764 in operable communication with the camera control computer 22. The function of the microcontroller 764 is to receive timing/sychronization signals and control data

from the camera control computer 22 in order to precisely control the amount of current flowing through each VLD at each instant in time. Fig. 1I15E graphically illustrates an exemplary triangular current waveform which might be transmitted across the junction of each VLD in the PLIA of Fig. 1I15C, as the current waveform is being controlled by the microcontroller 764, voltage source 762 and digitally-controllable potentiometer 763 associated with the VLD 13. Fig. 1I15F graphically illustrates the light intensity output from each VLD in the PLIA of Fig. 1I15C, generated in response to the triangular electrical current waveform transmitted across the junction of the VLD.

Notably, the current waveforms generated by the microcontroller 764 can be quite diverse in character, in order to produce temporal intensity modulation functions (TIMF) which exhibit a spectral harmonic constitution that results in a substantial reduction in the RMS power of speckle-pattern noise observed at the image detection array of PLIIM-based systems.

In accordance with the second generalized method of the present invention, each VLD 13 is preferably driven in a non-linear manner by a time-varying electrical current produced by a high-speed VLD drive current modulation circuit, referred to as the TIM controller 761 in Figs. 1I15C and 1I15D. In the illustrative embodiment shown in Figs. 1I15C through 1I15F, the electrical current flowing through each VLD 13 is controlled by the digitally-controllable potentiometer 763 configured in electrical series therewith, and having an electrical resistance value R programmably set under the control of microcontroller 753. Notably, microcontroller 764 automatically responds to timing/synchronization signals and control data periodically received from the camera control computer 22 prior to the capture of each line of digital image data by the PLIIM-based system. The VLD drive current supplied to each VLD in the PLIA effectively modulates the amplitude of the output planar laser illumination beam (PLIB) component. Preferably, the depth of amplitude modulation (AM) of each output PLIB component will be close or equal to 100% in order to increase the magnitude of the higher order spectral harmonics generated during the AM process. Increasing the rate of change of the amplitude modulation of the laser beam (i.e. its pulse repetition frequency) will result in the generation of higher-order spectral components in the composite PLIB. Shortening the width of each optical pulse in the output pulse train of the transmitted PLIB will increase the magnitude of the higher-order spectral harmonics present therein during object illumination operations.

In the case of optical system of Fig. 1I15C, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated during each photo-integration time period: (i) the time duration of each light pulse in the output PLIB 443; (ii) the rate of repetition of the light pulses in the output PLIB; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (i) and (ii) will factor into the specification of the temporal intensity

modulation function (TIMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I14A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the temporal derivative of the temporal intensity modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Notably, both external-type and internal-type laser modulation devices can be used to generate higher order spectral harmonics within transmitted PLIBs. Internal-type laser modulation devices, employing laser current and/or temperature control techniques, modulate the temporal intensity of the transmitted PLIB in a non-linear manner (i.e. zero PLIB power, full PLIB power) by controlling the current of the VLDs producing the PLIB. In contrast, external-type laser modulation devices, employing high-speed optical-gating and other light control devices, modulate the temporal intensity of the transmitted PLIB in a non-linear manner (i.e. zero PLIB power, full PLIB power) by directly controlling temporal intensity of luminous power in the transmitted PLIB. Typically, such external-type techniques will require additional heat management apparatus. Cost and spatial constraints will factor in which techniques to use in a particular application.

<u>Third Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Temporal-Coherence Of The Planar Laser Illumination Beam (PLIB) Before It Illuminates The Target Object By Applying Temporal Phase Modulation Techniques During The Transmission Of The PLIB Towards The Target</u>

Referring to Figs. 1I16 through 1I17E, the third generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of temporal phase modulating the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object therewith so that the object is illuminated with a temporally coherent reduced planar laser beam and, as a result, numerous time-varying (random) speckle-noise patterns are produced and detected over the photo-

integration time period of the image detection array (in the IFD subsystem), thereby allowing these speckle-noise patterns to be temporally averaged and/or spatially averaged and the observable speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I16B, the first step of the third generalized method shown in Figs. 1I16 through 1I16A involves temporal phase modulating the transmitted PLIB along the entire extent thereof according to a (random or periodic) temporal phase modulation function (TPMF) prior to illumination of the target object with the PLIB, so as to produce numerous substantially different time-varying speckle-noise pattern at the image detection array of the IFD Subsystem during the photo-integration time period thereof. As indicated at Block B in Fig. 1I16B, the second step of the method involves temporally and spatially averaging the numerous substantially different speckle-noise patterns produced at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

When using the third generalized method, the target object is repeatedly illuminated with laser light apparently originating from different moments (i.e. virtual illumination sources) in time over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered temporally incoherent with each other. On a time-average basis, these time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of speckle-noise patterns observed thereat. As speckle-noise patterns are roughly uncorrelated at the image detection array, the reduction in speckle-noise power should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the images frame thereof. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The third generalized method above can be explained in terms of Fourier Transform optics. When temporal intensity modulating the transmitted PLIB by a periodic or random temporal phase modulation function (TPMF), while satisfying conditions (i) and (ii) above, a temporal phase modulation process occurs on the temporal domain. This temporal phase modulation process is equivalent to mathematically multiplying the transmitted PLIB by the temporal phase modulation function. This multiplication process on the temporal domain is

equivalent on the temporal-frequency domain to the convolution of the Fourier Transform of the temporal phase modulation function with the Fourier Transform of the composite PLIB. On the temporal-frequency domain, this convolution process generates temporally-incoherent (i.e. statistically-uncorrelated or independent) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of each detector element, to reduce the speckle-noise pattern observed at the image detection array.

In general, various types of spatial light modulation techniques can be used to carry out the third generalized method including, for example: an optically resonant cavity (i.e. etalon device) affixed to external portion of each VLD; a phase-only LCD (PO-LCD) temporal intensity modulation panel; and fiber optical arrays. Several of these temporal phase modulation mechanisms will be described in detail below.

Electrically-Passive Optical Apparatus Of The Present Invention For Temporal Phase Modulating The Planar Laser Illumination Beam (PLIB) Prior To Target Object Illumination Employing Photon Trapping, Delaying And Releasing Principles Within An Optically-Reflective Cavity (i.e. Etalon) Externally Affixed To Each Visible Laser Diode Within The Planar Laser Illumination Array (PLIA)

In Figs. 1I17A through 1I17B, there is shown an optical assembly 430 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 430 comprises a PLIA 6A, 6B with a refractive-type cylindrical lens array 431 (e.g. operating according to refractive, diffractive and/or reflective principles) supported within frame 432, and an electrically-passive temporal phase modulation device (i.e. etalon) 433 realized as an external optically reflective cavity) affixed to each VLD 13 of the PLIA 6A, 6B.

The primary principle of this temporal phase modulation technique is to delay portions of the laser light (i.e. photons) emitted by each laser diode 13 by times longer than the inherent temporal coherence length of the laser diode. In this embodiment, this is achieved by employing photon trapping, delaying and releasing principles within an optically reflective cavity. Typical laser diodes have a coherence length of a few centimeters (cm). Thus, if some of the laser illumination can be delayed by the time of flight of a few centimeters, then it will be incoherent with the original laser illumination. The electrically-passive device 433 shown in Fig. 1I17B can be realized by a pair of parallel, reflective surfaces (e.g. plates, films or layers) 436A and 436B, mounted to the output of each VLD 13 in the PLIA 6A, 6B. If one surface is essentially totally reflective (e.g. 97% reflective) and the other about 94% reflective, then about 3% of the laser illumination (i.e. photons) will escape the device through the partially reflective surface of the

device on each round trip. The laser illumination will be delayed by the time of flight for one round trip between the plates. If the plates 436A and 436B are separated by a space 437 of several centimeters length, then this delay will be greater than the coherence time of the laser source. In the illustrative embodiment of Figs. 1I17A and 1I17B, the emitted light (i.e. photons) will make about thirty (30) trips between the plates. This has the effect of mixing thirty (30) photon distribution samples from the laser source, each sample residing outside the coherence time thereof, thus destroying or substantially reducing the temporal coherence of the laser beams produced from the laser illumination sources in the PLIA of the present invention. A primary advantage of this technique is that it employs electrically-passive components which might be manufactured relatively inexpensively in a mass-production environment. Suitable components for constructing such electrically-passive temporal phase modulation devices 433 can be obtained from various commercial vendors.

During operation, the transmitted PLIB 434 is temporal phase modulated according to a (random or periodic) temporal phase modulation function (TPMF) so that the phase along the wavefront of the PLIB is modulated and numerous substantially different time-varying speckle-noise patterns are produced at the image detection array during the photo-integration time period thereof. The time-varying speckle-noise patterns detected at the image detection array are temporally and spatially averaged during each photo-integration time period thereof, thus reducing the RMS power of the speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I17A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated during each photo-integration time period: (i) the spacing between reflective surfaces (e.g. plates, films or layers) 436A and 436B; (ii) the reflection coefficients of these reflective surfaces; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (i) and (ii) will factor into the specification of the temporal phase modulation function (TPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I17A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be

expressed mathematically in terms of (i) the time derivative of the temporal phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Temporal Phase Modulating The Planar Laser Illumination Beam (PLIB) Using A Phase-Only LCD-Based (PO-LCD) Temporal Phase Modulation Panel Prior To Target Object Illumination</u>

As shown in Fig. 1I17C, the general phase modulation principles embodied in the apparatus of Fig. 1I8A can be applied in the design the optical assembly for reducing the RMS power of speckle-noise patterns observed at the image detection array of a PLIIM-based system. As shown in Fig. 1I17C, optical assembly 800 comprises: a backlit transmissive-type phase-only LCD (PO-LCD) temporal phase modulation panel 701 mounted slightly beyond a PLIA 6A, 6B to intersect the composite PLIB 702; and a cylindrical lens array 703 supported in frame 704 and mounted closely to, or against phase modulation panel 701. In the illustrative embodiment, the phase modulation panel 701 comprises an array of vertically arranged phase modulating elements or strips 705, each made from birefrigent liquid crystal material which is capable of imparting a phase delay at each control point along the PLIB wavefront, which is greater than the coherence length of the VLDs using in the PLIA. Under the control of camera control computer 22, programmed drive voltage circuitry 706 supplies a set of phase control voltages to the array 705 so as to controllably vary the drive voltage applied across the pixels associated with each predefined phase modulating element 705.

During system operation, the phase-modulation panel 701 is driven by applying substantially the same control voltage across each element 705 in the phase modulation panel 701 so that the temporal phase along the entire wavefront of the PLIB is modulated by substantially the same amount of phase delay. These temporally-phase modulated PLIB components are optically combined by the cylindrical lens array 703, and projected 703 onto the same points on the surface of the object being illuminated. This illumination process results in producing numerous substantially different time-varying speckle-noise patterns at the image detection array (of the accompanying IFD subsystem) during the photo-integration time period thereof. These time-varying speckle-noise patterns are temporally and possibly spatially averaged thereover, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I17C, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated during each photo-integration time period: (i) the number of phase modulating elements in the array; (ii) the amount of temporal phase delay introduced at each control point along the wavefront; (iii) the

rate at which the temporal phase delay changes; and (iv) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the temporal phase modulation function (TPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I17C, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the time derivative of the temporal phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Temporal Phase Modulating The Planar Laser Illumination (PLIB) Using A High-Density Fiber-Optic Array Prior To Target Object Illumination</u>

As shown in Figs. 1I17D and 1I17E, temporal phase modulation principles can be applied in the design of an optical assembly for reducing the RMS power of speckle-noise patterns observed at the image detection array of a PLIIM-based system. As shown in Figs. 1I17C and 1I17C, optical assembly 810 comprises: a high-density fiber optic array 811 mounted slightly beyond a PLIA 6A, 6B, wherein each optical fiber element intersects a portion of a PLIB component 812 (at a particular phase control point) and transmits a portion of the PLIB component therealong while introducing a phase delay greater than the temporal coherence length of the VLDs, but different than the phase delay introduced at other phase control points; and a cylindrical lens array 703 characterized by a high spatial frequency, and supported in frame 704 and either mounted closely to or optically interfaced with the fiber optic array (FOA) 811, for the purpose of optically combining the differently phase-delayed PLIB subcomponents and projecting these optical combined components onto the same points on the target object to be illuminated. Preferably, the diameter of the individual fiber optical elements in the FOA 811 is sufficiently small to form a tightly packed fiber optic bundle with a rectangular form factor having a width dimension about the same size as the width of the cylindrical lens array 703, and

a height dimension high enough to intercept the entire heightwise dimension of the PLIB components directed incident thereto by the corresponding PLIA. Preferably, the FOA 811 will have hundreds, if not thousands of phase control points at which different amounts of phase delay can be introduced into the PLIB. The input end of the fiber optic array can be capped with an optical lens element to optimize the collection of light rays associated with the incident PLIB components, and the coupling of such rays to the high-density array of optical fibers embodied therewithin. Preferably, the output end of the fiber optic array is optically coupled to the cylindrical lens array to minimize optical losses during PLIB propagation from the FOA through the cylindrical lens array.

During system operation, the FOA 811 modulates the temporal phase along the wavefront of the PLIB by introducing (i.e. causing) different phase delays along different phase control points along the PLIB wavefront, and these phase delays are greater than the coherence length of the VLDs employed in the PLIA. The cylindrical lens array optically combines numerous phase-delayed PLIB subcomponents and projects them onto the same points on the surface of the object being illuminated, causing such points to be illuminated by a temporal coherence reduced PLIB. This illumination process results in producing numerous substantially different time-varying speckle-noise patterns at the image detection array (of the accompanying IFD subsystem) during the photo-integration time period thereof. These time-varying speckle-noise patterns are temporally and possibly spatially averaged thereover, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I17C, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the number and diameter of the optical fibers employed in the FOA; (ii) the amount of phase delay introduced by fiber optical element, in comparison to the coherence length of the corresponding VLD; (iii) the spatial period of the cylindrical lens array; (iv) the number of temporal phase control points along the PLIB; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (v) will factor into the specification of the temporal phase modulation function (TPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I17C, the number of substantially different time-varying speckle-noise pattern samples which need to be

generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the time derivative of the temporal phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Fourth Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Temporal Coherence Of The Planar Laser Illumination Beam (PLIB) Before It Illuminates The Target Object By Applying Temporal Frequency Modulation Techniques During The Transmission Of The PLIB Towards The Target</u>

Referring to Figs. 1I18A through 1I19C, the fourth generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of temporal frequency modulating the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object therewith so that the object is illuminated with a temporally coherent reduced planar laser beam and, as a result, numerous time-varying (random) speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array (in the IFD subsystem), thereby allowing these speckle-noise patterns to be temporally averaged and/or spatially averaged and the observable speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I18B, the first step of the fourth generalized method shown in Figs. 1I18 through 1I18A involves modulating the temporal frequency of the transmitted PLIB along the entire extent thereof according to a (random or periodic) temporal frequency modulation function (TFMF) prior to illumination of the target object with the PLIB, so as to produce numerous substantially different time-varying speckle-noise pattern at the image detection array of the IFD Subsystem during the photo-integration time period thereof. As indicated at Block B in Fig. 1I18B, the second step of the method involves temporally and spatially averaging the numerous substantially different speckle-noise patterns produced at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

When using the fourth generalized method, the target object is repeatedly illuminated with laser light apparently originating from different moments (i.e. virtual illumination sources) in time over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector

element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual illumination sources are effectively rendered temporally incoherent with each other. On a time-average basis, these virtual illumination sources produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of speckle-noise patterns observed thereat. As speckle-noise patterns are roughly uncorrelated at the image detection array, the reduction in speckle-noise power should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the images frame thereof. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The fourth generalized method above can be explained in terms of Fourier Transform optics. When temporal intensity modulating the transmitted PLIB by a periodic or random temporal frequency modulation function (TFMF), while satisfying conditions (i) and (ii) above, a temporal frequency modulation process occurs on the temporal domain. This temporal modulation process is equivalent to mathematically multiplying the transmitted PLIB by the temporal frequency modulation function. This multiplication process on the temporal domain is equivalent on the temporal-frequency domain to the convolution of the Fourier Transform of the temporal frequency modulation function with the Fourier Transform of the composite PLIB. On the temporal-frequency domain, this convolution process generates temporally-incoherent (i.e. statistically-uncorrelated or independent) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of each detector element, to reduce the speckle-noise pattern observed at the image detection array.

In general, various types of spatial light modulation techniques can be used to carry out the third generalized method including, for example: junction-current control techniques for periodically inducing VLDs into a mode of frequency hopping, using thermal feedback; and multi-mode visible laser diodes (VLDs) operated just above their lasing threshold. Several of these temporal frequency modulation mechanisms will be described in detail below.

<u>Electro-Optical Apparatus Of The Present Invention For Temporal Frequency Modulating The Planar Laser Illumination Beam (PLIB) Prior To Target Object Illumination Employing Drive-Current Modulated Visible Laser Diodes (VLDs)</u>

In Figs. 1I19A and 1I19B, there is shown an optical assembly 450 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 450 comprises a stationary cylindrical lens array 451 (e.g. operating according to refractive, diffractive and/or reflective principles), supported in a frame 452 and mounted in front of a PLIA 6A, 6B embodying a plurality of drive-current modulated visible laser diodes (VLDs) 13. In accordance with the second generalized method of the present invention, each VLD 13 is driven in a non-linear manner by an electrical time-varying current produced by a high-speed VLD drive current modulation circuit 454, In the illustrative embodiment, the VLD drive current modulation circuit 454 is supplied with DC power from a DC power source 403 and operated under the control of camera control computer 22. The VLD drive current supplied to each VLD effectively modulates the amplitude of the output laser beam 456. Preferably, the depth of amplitude modulation (AM) of each output laser beam will be close to 100% in order to increase the magnitude of the higher order spectral harmonics generated during the AM process. As mentioned above, increasing the rate of change of the amplitude modulation of the laser beam will result in higher order optical components in the composite PLIB.

In alternative embodiments, the high-speed VLD drive current modulation circuit 454 can be operated (under the control of camera control computer 22 or other programmed microprocessor) so that the VLD drive currents generated by VLD drive current modulation circuit 454 periodically induce "spectral mode-hopping" within each VLD numerous time during each photo-integration time interval of the PLIIM-based system. This will cause each VLD to generate multiple spectral components within each photo-integration time period of the image detection array.

Optionally, the optical assembly 450 may further comprise a VLD temperature controller 456, operably connected to the camera controller 22, and a plurality of temperature control elements 457 mounted to each VLD. The function of the temperature controller 456 is to control the junction temperature of each VLD. The camera control computer 22 can be programmed to control both VLD junction temperature and junction current so that each VLD is induced into modes of spectral hopping for a maximal percentage of time during the photo-integration time period of the image detector. The result of such spectral mode hopping is to cause temporal frequency modulation of the transmitted PLIB 458, thereby enabling the generation of numerous time-varying speckle-noise patterns at the image detection array, and the temporal and spatial averaging of these patterns during the photo-integration time period of the array to reduce the RMS power of speckle-noise patterns observed at the image detection array.

Notably, in some embodiments, it may be preferred that the cylindrical lens array 451 be realized using light diffractive optical materials so that each spectral component within the transmitted PLIB will be diffracted at slightly different angles dependent on its optical

wavelength, causing the PLIB to undergo micro-movement during target illumination operations. In some applications, such as the one shown in Figs. 1I25M1 and 1I25M2, such wavelength dependent movement can be used to modulate the spatial phase of the PLIB wavefront along directions either within the plane of the PLIB or orthogonal thereto, depending on how the diffractive-type cylindrical lens array is designed. In such applications, both temporal frequency modulation and spatial phase modulation of the PLIB wavefront would occur, thereby creating a hybrid-type despeckling scheme.

<u>Electro-Optical Apparatus Of The Present Invention For Temporal Frequency Modulating The Planar Laser Illumination Beam (PLIB) Prior To Target Object Illumination Employing Multi Mode Visible Laser Diodes (VLDs) Operated Just Above Their Lasing Threshold</u>

In Figs. 1I19C, there is shown an optical assembly 450 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 450 comprises a stationary cylindrical lens array 451 (e.g. operating according to refractive, diffractive and/or reflective principles), supported in a frame 452 and mounted in front of a PLIA 6A, 6B embodying a plurality of "multi-mode" type visible laser diodes (VLDs) operated just above their lasing threshold so that each multi-mode VLD produces a temporal coherence-reduced laser beam. The result of producing temporal coherence-reduced PLIBs from each PLIA using this method is that numerous time-varying speckle-noise patterns are produced at the image detection array during target illumination operations. Therefore these speckle-patterns are temporally and spatially averaged at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of observed speckle-noise patterns.

<u>Fifth Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Spatial Coherence Of The Planar Laser Illumination Beam (PLIB) Before It Illuminates The Target Object By Applying Spatial Intensity Modulation Techniques During The Transmission Of The PLIB Towards The Target</u>

Referring to Figs. 1I20 through 1I21D, the fifth generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of modulating the spatial intensity of the wavefront of the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object (e.g. package) therewith so that the object is illuminated with a spatially coherent-reduced planar laser beam. As a result, numerous substantially different time-varying speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array (in the IFD subsystem). These speckle-noise patterns are temporally averaged and possibly spatially averaged over the photo-integration time period and the RMS power of observable

speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I20B, the first step of the fifth generalized method shown in Figs. 1I20 and 1I20A involves modulating the spatial intensity of the transmitted planar laser illumination beam (PLIB) along the planar extent thereof according to a (random or periodic) spatial intensity modulation function (SIMF) prior to illumination of the target object with the PLIB, so as to produce numerous substantially different time-varying speckle-noise pattern at the image detection array of the IFD Subsystem during the photo-integration time period thereof. As indicated at Block B in Fig. 1I20B, the second step of the method involves temporally and spatially averaging the numerous substantially different speckle-noise patterns produced at the image detection array in the IFD Subsystem during the photo-integration time period thereof.

When using the fifth generalized method, the target object is repeatedly illuminated with laser light apparently originating from different points (i.e. virtual illumination sources) in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual illumination sources are effectively rendered spatially incoherent with each other. On a time-average basis, these virtual illumination sources produce time-varying speckle-noise patterns which are temporally (and possibly spatially) averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of the speckle-noise pattern (i.e. level) observed thereat. As speckle noise patterns are roughly uncorrelated at the image detection array, the reduction in speckle-noise power should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the image frame thereof. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The fifth generalized method above can be explained in terms of Fourier Transform optics. When spatial intensity modulating the transmitted PLIB by a periodic or random spatial intensity modulation function (SIMF), while satisfying conditions (i) and (ii) above, a spatial intensity modulation process occurs on the spatial domain. This spatial intensity modulation process is equivalent to mathematically multiplying the transmitted PLIB by the spatial intensity modulation function. This multiplication process on the spatial domain is equivalent on the spatial-frequency domain to the convolution of the Fourier Transform of the spatial

intensity modulation function with the Fourier Transform of the transmitted PLIB. On the spatial-frequency domain, this convolution process generates spatially-incoherent (i.e. statistically-uncorrelated) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally (and possibly) spatially averaged during the photo-integration time period of each detector element, to reduce the RMS power of the speckle-noise pattern observed at the image detection array.

In general, various types of spatial intensity modulation techniques can be used to carry out the fifth generalized method including, for example: a pair of comb-like spatial intensity modulating filter arrays reciprocated relative to each other at a high-speeds; rotating spatial filtering discs having multiple sectors with transmission apertures of varying dimensions and different light transmittivity to spatial intensity modulate the transmitted PLIB along its wavefront; a high-speed LCD-type spatial intensity modulation panel; and other spatial intensity modulation devices capable of modulating the spatial intensity along the planar extent of the PLIB wavefront. Several of these spatial light intensity modulation mechanisms will be described in detail below.

Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Spatial Intensity Modulation (SIM) Panels With Respect To The Cylindrical Lens Arrays So As To Spatial Intensity Modulate The Wavefront Of The Planar Laser Illumination Beam (PLIB) Prior To Target Object Illumination

In Figs. 1I21 through 1I21D, there is shown an optical assembly 730 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 730 comprises a PLIA 6A with a pair of spatial intensity modulation (SIM) panels 731A and 731B, and an electronically-controlled mechanism 732 for micro-oscillating SIM panels 731A and 731B, behind a cylindrical lens array 733 mounted within a support frame 734 with the SIM panels. Each SIM panel comprises an array of light intensity modifying elements 735, each having a different light transmittivity value (e.g. measured against a grey-scale) to impart a different degree of intensity modulation along the wavefront of the composite PLIB 738 transmitted through the SIM panels. The width dimensions of each SIM element 735, and their spatial periodicity, may be determined by the spatial intensity modulation requirements of the application at hand. In some embodiments, the width of each SIM element 735 may be random or aperiodically arranged along the linear extent of each SIM panel. In other embodiments, the width of the SIM elements may be similar and periodically arranged along each SIM panel. As shown in Fig. 1I19C, support frame 734 has a light transmission window 740, and mounts the SIM panels 731A and 731B in a relative reciprocating manner, behind the cylindrical lens array

733, and two pairs of ultrasonic (or other motion) transducers 736A, 736B, and 737A, 737B arranged (90 degrees out of phase) in a push-pull configuration, as shown in Fig. 1I21D.

In accordance with the fifth generalized method, the SIM panels 731A and 731B are micro-oscillated, relative to each other (out of phase by 90 degrees) using motion transducers 736A, 736B, and 737A, 737B. During operation of the mechanism, the individual beam components within the composite PLIB 738 are transmitted through the reciprocating SIM panels 731A and 731B, and micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity $v(t)$ which causes the spatial intensity along the wavefronts of the transmitted PLIB 739 to be modulated. The cylindrical lens array 733 optically combines numerous phase modulated PLIB components and projects them onto the same points on the surface of the target object to be illuminated. This coherence-reduced illumination process causes numerous substantially different time-varying speckle-noise patterns to be generated at the image detection array of the PLIIM-based during the photo-integration time period thereof. The time-varying speckle-noise patterns produced at the image detection array are temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I21A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial frequency and light transmittance values of the SIM panels 731A, 731B; (ii) the length of the cylindrical lens array 733 and the SIM panels; (iii) the relative velocities thereof; and (iv) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. In general, if a system requires an increase in reduction in speckle-noise at the image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period of the image detection array employed in the system. Parameters (1) through (iii) will factor into the specification of the spatial intensity modulation function (SIMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I21A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be

experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial intensity modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Sixth Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Spatial-Coherence Of The Planar Laser Illumination Beam (PLIB) After It Illuminates The Target By Applying Spatial Intensity Modulation Techniques During The Detection Of The Reflected/Scattered PLIB</u>

Referring to Figs. 1I22 through 1I23B, the sixth generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of spatial-intensity modulating the composite-type "return" PLIB produced when the transmitted PLIB illuminates and reflects and/or scatters off the target object. The return PLIB constitutes a spatially coherent-reduced laser beam and, as a result, numerous time-varying speckle-noise patterns are detected over the photo-integration time period of the image detection array in the IFD subsystem. These time-varying speckle-noise patterns are temporally and/or spatially averaged and the RMS power of observable speckle-noise patterns significantly reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I23B, the first step of the sixth generalized method shown in Figs. 1I22 through 1I23A involves spatially modulating the received PLIB along the planar extent thereof according to a (random or periodic) spatial- intensity modulation function (SIMF) after illuminating the target object with the PLIB, so as to produce numerous substantially different time-varying speckle-noise patterns during each photo-integration time period of the image detection array of the PLIIM-based system. As indicated at Block B in Fig. 1I22B, the second step of the method involves temporally and spatially averaging these time-varying speckle-noise patterns during the photo-integration time period of the image detection array, thus reducing the RMS power of speckle-noise patterns observed at the image detection array.

When using the sixth generalized method, the image detection array in the PLIIM-based system repeatedly detects laser light apparently originating from different points in space (i.e. from different virtual illumination sources) over the photo-integration period of each detector element in the image detection array. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image

detection element, these virtual illumination sources are effectively rendered spatially incoherent (or spatially coherent-reduced) with respect to each other. On a time-average basis, these virtual illumination sources produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of the image detection array, thereby reducing the RMS power of speckle-noise patterns observed thereat. As speckle noise patterns are roughly uncorrelated at the image detector, the reduction in speckle-noise power should be proportional to the square root of the number of independent real and virtual laser illumination sources contributing to formation of the image frames of the target object. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The sixth generalized method above can be explained in terms of Fourier Transform optics. When spatially modulating a return PLIB by a periodic or random spatial modulation (i.e. windowing) function, while satisfying conditions (i) and (ii) above, a spatial intensity modulation process occurs on the spatial domain. This spatial intensity modulation process is equivalent to mathematically multiplying the composite return PLIB by the spatial intensity modulation function (SIMF). This multiplication process on the spatial domain is equivalent on the spatial-frequency domain to the convolution of the Fourier Transform of the spatial intensity modulation function with the Fourier Transform of the return PLIB. On the spatial-frequency domain, this equivalent convolution process generates spatially-incoherent (i.e. statistically-uncorrelated) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of each detector element, to reduce the RMS power of speckle-noise patterns observed at the image detection array.

In general, various types of spatial intensity modulation techniques can be used to carry out the sixth generalized method including, for example: high-speed electro-optical (e.g. ferro-electric, LCD, etc.) dynamic spatial filters, located before the image detector along the optical axis of the camera subsystem; physically rotating spatial filters, and any other spatial intensity modulation element arranged before the image detector along the optical axis of the camera subsystem, through which the received PLIB beam may pass during illumination and image detection operations for spatial intensity modulation without causing optical image distortion at the image detection array. Several of these spatial intensity modulation mechanisms will be described in detail below.

Apparatus Of The Present Invention For Spatial-Intensity Modulating The Return Planar Laser Illumination Beam (PLIB) Prior To Detection At The Image Detector

In Figs. 1I22A, there is shown an optical assembly 460 for use at the IFD Subsystem in any PLIIM-based system of the present invention. As shown, the optical assembly 460 comprises an electro-optical mechanism 460 mounted before the pupil of the IFD Subsystem for the purpose of generating a rotating a spatial intensity modulation structure (e.g. maltese-cross aperture) 461. The return PLIB 462 is spatial intensity modulated at the IFD subsystem in accordance with the principles of the present invention, with introducing significant image distortion at the image detection array. The electro-optical mechanism 460 can be realized using a high-speed liquid crystal (LC) spatial intensity modulation panel 463 which is driven by a LCD driver circuit 464 so as to realize a maltese-cross aperture (or other spatial intensity modulation structure) before the camera pupil that rotates about the optical axis of the IFD subsystem during object illumination and imaging operations. In the illustrative embodiment, the maltese-cross aperture pattern has 100% transmittivity, against an optically opaque background. Preferably, the physical dimensions and angular velocity of the maltese-cross aperture 461 will be sufficient to achieve a spatial intensity modulation function (SIMF) suitable for speckle-noise pattern reduction in accordance with the principles of the present invention.

In Figs. 1I22B, there is shown a second optical assembly 470 for use at the IFD Subsystem in any PLIIM-based system of the present invention. As shown, the optical assembly 470 comprises an electro-mechanical mechanism 471 mounted before the pupil of the IFD Subsystem for the purpose of generating a rotating maltese-cross aperture 472, so that the return PLIB 473 is spatial intensity modulated at the IFD subsystem in accordance with the principles of the present invention. The electro-mechanical mechanism 471 can be realized using a high-speed electric motor 474, with appropriate gearing 475, and a rotatable maltese-cross aperture stop 476 mounted within a support mount 477. In the illustrative embodiment, the maltese-cross aperture pattern has 100% transmittivity, against an optically opaque background. As a motor drive circuit 478 supplies electrical power to the electrical motor 474, the motor shaft rotates, turning the gearing 475, and thus the maltese-cross aperture stop 476 about the optical axis of the IFD subsystem. Preferably, the maltese-cross aperture 476 will be driven to an angular velocity which is sufficient to achieve the spatial intensity modulation function required for speckle-noise pattern reduction in accordance with the principles of the present invention.

In the case of the optical systems of Figs. 1I23A and 1I23B, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial

dimensions and relative physical position of the apertures used to form the spatial intensity modulation structure 461, 472; (ii) the angular velocity of the apertures in the rotating structures; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (i) through (ii) will factor into the specification of the spatial intensity modulation function (SIMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the systems of Figs. 1I23A and 1I23B, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the spatial gradient of the spatial intensity modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Seventh Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Temporal Coherence Of The Planar Laser Illumination Beam (PLIB) After It Illuminates The Target By Applying Temporal Intensity Modulation Techniques During The Detection Of The Reflected/Scattered PLIB</u>

Referring to 1I24 through 1I24C, the seventh generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of temporal intensity modulating the composite-type "return" PLIB produced when the transmitted PLIB illuminates and reflects and/or scatters off the target object. The return PLIB constitutes a temporally coherent-reduced laser beam. As a result, numerous time-varying (random) speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array (in the IFD subsystem). These time-varying speckle-noise patterns are temporally and/or spatially averaged and the observable speckle-noise patterns significantly reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I24B, the first step of the seventh generalized method shown in Figs. 1I24 and 1I24A involves modulating the temporal phase of the received PLIB along the planar extent thereof according to a (random or periodic) temporal intensity modulation function (TIMF) after illuminating the target object with the PLIB, so as to produce numerous substantially different time-varying speckle-noise patterns during each photo-integration time period of the image detection array of the PLIIM-based system. As indicated at Block B in Fig. 1I24B, the second step of the method involves temporally and spatially averaging these time-varying speckle-noise patterns during the photo-integration time period of the image detection array, thus reducing the RMS power of speckle-noise patterns observed at the image detection array.

When using the seventh generalized method, the image detector of the IFD subsystem repeatedly detects laser light apparently originating from different moments in space (i.e. virtual illumination sources) over the photo-integration period of each detector element in the image detection array of the PLIIM system. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual illumination sources are effectively rendered temporally incoherent with each other. On a time-average basis, these virtual illumination sources produce time-varying speckle-noise patterns which can be temporally and spatially averaged during the photo-integration time period of the image detection elements, thereby reducing the speckle-noise pattern (i.e. level) observed thereat. As speckle noise patterns are roughly uncorrelated at the image detector, the reduction in speckle-noise power should be proportional to the square root of the number of independent real and virtual laser illumination sources contributing to formation of the image frames of the target object. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

In general, various types of temporal intensity modulation techniques can be used to carry out the method including, for example: high-speed temporal intensity modulators such as electro-optical shutters, pupils, and stops, located along the optical path of the composite return PLIB focused by the IFD subsystem; etc.

<u>Electro-Optical Apparatus Of The Present Invention For Temporal Intensity Modulating The Planar Laser Illumination Beam (PLIB) Prior To Detecting Images By Employing High-Speed Light Gating/Switching Principles</u>

In Fig. 1I24C, there is shown an optical assembly 480 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 480 comprises a high-speed electro-optical temporal intensity modulation panel (e.g. high-speed electro-optical gating/switching

panel) 481, mounted along the optical axis of the IFD Subsystem, before the imaging optics thereof. A suitable high-speed temporal intensity modulation panel 481 for use in carrying out this particular embodiment of the present invention might be made using liquid crystal, ferro-electric or other high-speed light control technology. During operation, the received PLIB is temporal intensity modulated as it is transmitted through the temporal intensity modulation panel 481. During temporal intensity modulation process at the IFD subsystem, numerous substantially different time-varying speckle-noise patterns are produced. These speckle-noise patterns are temporally and spatially averaged at the image detection array 3A during each photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

The time characteristics of the temporal intensity modulation function (TIMF) created by the temporal intensity modulation panel 481 will be selected in accordance with the principles of the present invention. Preferably, the time duration of the light transmission window of the TIMF will be relatively short, and repeated at a relatively high rate with respect to the inverse of the photo-integration time period of the image detector so that many spectral-harmonics will be generated during each such time period, thus producing many time-varying speckle-noise patterns at the image detection array. Thus, if a particular imaging application at hand requires a very short photo-integration time period, then it is understood that the rate of repetition of the light transmission window of the TIMP (and thus the rate of switching/gating electro-optical panel 481) will necessarily become higher in order to generate sufficiently weighted spectral components on the time-frequency domain required to reduce the temporal coherence of the received PLIB falling incident at the image detection array.

In the case of the optical system of Fig. 1I24C, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the time duration of the light transmission window of the TIMF realized by temporal intensity modulation panel 481; (ii) the rate of repetition of the light duration window of the TIMF; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (i) through (ii) will factor into the specification of the TIMF of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrelated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I24C, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathematically in terms of (i) the time derivative of the temporal phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

While the speckle-noise pattern reduction (i.e. despeckling) techniques described above have been described in conjunction with the system of Fig. 1A for purposes of illustration, it is understood that that any of these techniques can be used in conjunction with any of the PLIIM-based systems of the present invention, and are hereby embodied therein by reference thereto as if fully explained in conjunction with its structure, function and operation.

PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A Micro-Oscillating Cylindrical Lens Array Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent To Produce Spatial-Incoherent PLIB Components And Optically Combines And Projects Said Spatially-Incoherent PLIB Component Onto The Same Points On An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Structure Micro-Oscillates The PLIB Components Transversely Along The Direction Orthogonal To Said Planar Extent, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Spatially Incoherence Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25A1 and 1I25A2, there is shown a PLIIM-based system of the present invention 860 having an speckle-pattern noise reduction subsystem embodied therewithin, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench on opposite sides of the IFD module 861; and (iii) a 2-D PLIB micro-oscillation mechanism 866 arranged with each PLIM 865A and 865B in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 866 comprises: a micro-oscillating cylindrical lens array 867 as shown in Figs. 1I3A through 1I3D, and a micro-oscillating PLIB reflecting mirror 868 configured therewith. As shown in Fig. 1I25A2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB 869 is transmitted perpendicularly through cylindrical lens array 867, whereas the FOV of the image detection array 863 is disposed at a small acute angle so that the PLIB and FOV converge on the

micro-oscillating mirror element 868 so that the PLIB and FOV maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. As shown, these optical components are configured together as an optical assembly for the purpose of micro-oscillating the PLIB 869 laterally along its planar extent as well as transversely along the direction orthogonal thereto, so that during illumination operations, the PLIB 870 is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal thereto. This causes the phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. During object illumination operations, these numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A First Micro-Oscillating Light Reflective Element Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent To Produce Spatially Incoherent PLIB Components, A Second Micro-Oscillating Light Reflecting Element Micro-Oscillates The Spatially-Incoherent PLIB Components Transversely Along The Direction Orthogonal To Said Planar Extent, And Wherein A Stationary Cylindrical Lens Array Optically Combines And Projects Said Spatially-Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By Spatial Incoherent Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25B1 and 1I25B2, there is shown a PLIIM-based system of the present invention 875 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench 862 on opposite sides of the IFD module; and (iii) a 2-D PLIB micro-oscillation mechanism 876 arranged with each PLIM in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 876 comprises: a stationary PLIB folding mirror 877, a micro-oscillating PLIB reflecting element 878, and a stationary cylindrical lens array 879 as shown in Figs. 1I5A through 1I5D. These optical component are configured together as an optical assembly as shown for the purpose of micro-oscillating the PLIB 880 laterally along its planar extent as well as transversely along the direction orthogonal thereto, so

that during illumination operations, the PLIB 881 transmitted from each PLIM is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal thereto. This causes the spatial phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. During object illumination operations, these numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein An Acousto-Optic Bragg Cell Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent To Produce Spatially Incoherent PLIB Components, A Stationary Cylindrical Lens Array Optically Combines and Projects Said Spatially Incoherent PLIB Components Onto The Same Points On The Surface On An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Structure Micro-Oscillates The Spatially Incoherent PLIB Components Transversely Along The Direction Orthogonal To Said Planar Extent, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I125C1 and 1I25C2, there is shown a PLIIM-based system of the present invention 885 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench on opposite sides of the IFD module; and (iii) a 2-D PLIB micro-oscillation mechanism 886 arranged with each PLIM in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 886 comprises: an acousto-optic Bragg cell panel 887 micro-oscillates a planar laser illumination beam (PLIB) 888 laterally along its planar extent to produce spatially incoherent PLIB components, as shown in Figs. 1I6A through 1I6B; a stationary cylindrical lens array 889 optically combines and projects said spatially incoherent PLIB components onto the same points on the surface of an object to be illuminated; and a micro-oscillating PLIB reflecting element 890 for micro-oscillating the PLIB components in a direction orthogonal to the planar extent of the PLIB. As shown in Fig. 1I25C2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB 888 is transmitted perpendicularly through the Bragg cell panel 887 and the cylindrical lens array 889, whereas the FOV of the image detection array 863 is disposed

at a small acute angle, relative to PLIB 888, so that the PLIB and FOV converge on the micro-oscillating mirror element 890. The PLIB and FOV maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. These optical elements are configured together as shown as an optical assembly for the purpose of micro-oscillating the PLIB laterally along its planar extent as well as transversely along the direction orthogonal thereto, so that during illumination operations, the PLIB transmitted from each PLIM is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal (i.e. transverse) thereto. This causes the phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. During target illumination operations, these numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A High-Resolution Deformable Mirror (DM) Structure Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent To Produce Spatially Incoherent PLIB Components, A Micro-Oscillating Light Reflecting Element Micro-Oscillates The Spatially Incoherent PLIB Components Transversely Along The Direction Orthogonal To Said Planar Extent, And Wherein A Stationary Cylindrical Lens Array Optically Combines and Projects The Spatially Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By Said Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25D1 and 1I25D2, there is shown a PLIIM-based system of the present invention 895 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench 862 on opposite sides of the IFD module; and (iii) a 2-D PLIB micro-oscillation mechanism 896 arranged with each PLIM in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 896 comprises: a stationary PLIB reflecting element 897; a micro-oscillating high-resolution deformable mirror (DM) structure 898 as shown in Figs. 1I7A through 1I7C; and a stationary cylindrical lens array 899. These optical components are configured together as an optical assembly as shown for the purpose of

micro-oscillating the PLIB 900 laterally along its planar extent as well as transversely along the direction orthogonal thereto, so that during illumination operations, the PLIB transmitted from each PLIM is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal (i.e. transverse) thereto. This causes the spatial phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. During target illumination operations, these numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A Micro-Oscillating Cylindrical Lens Array Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent To Produce Spatially Incoherent PLIB Components Which Are Optically Combined And Projected Onto The Same Points On The Surface Of An Object To Be Illuminated, And A Micro-Oscillating Light Reflective Structure Micro-Oscillates The Spatially Incoherent PLIB Components Transversely Along The Direction Orthogonal To Said Planar Extent As Well As The Field Of View (FOV) Of A Linear (1D) CCD Image Detection Array Having Vertically-Elongated Image Detection Elements, Whereby Said Linear CCD Image Detection Array Detects Time-Varying Speckle-Noise Patterns Produced By The Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25E1 and 1I25E2, there is shown a PLIIM-based system of the present invention 905 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench 862 on opposite sides of the IFD module; and (iii) a 2-D PLIB micro-oscillation mechanism 906 arranged with each PLIM in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 906 comprises: a micro-oscillating cylindrical lens array structure 907 as shown in Figs. 1I4A through 1I4D for micro-oscillating the PLIB 908 laterally along its planar extent; a micro-oscillating PLIB/FOV refraction element 909 for micro-oscillating the PLIB and the field of view (FOV) of the linear CCD image sensor 863 transversely along the direction orthogonal to the planar extent of the PLIB; and a stationary PLIB/FOV folding mirror 910 for folding jointly the micro-oscillated PLIB and FOV towards the object to be illuminated and imaged in accordance with the principles of the present invention. These optical components are configured together as an optical assembly as

shown for the purpose of micro-oscillating the PLIB laterally along its planar extent while micro-oscillating both the PLIB and FOV of the linear CCD image sensor transversely along the direction orthogonal thereto. During illumination operations, the PLIB transmitted from each PLIM is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal (i.e. transverse) thereto, causing the phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

<u>PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A Micro-Oscillating Cylindrical Lens Array Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent And Produces Spatially Incoherent PLIB Components Which Are Optically Combined And Project Onto The Same Points On The Surface Of An Object To Be Illuminated, A Micro-Oscillating Light Reflective Structure Micro-Oscillates Transversely Along The Direction Orthogonal To Said Planar Extent, Both PLIB And The Field Of View (FOV) Of A Linear (1D) CCD Image Detection Array Having Vertically-Elongated Image Detection Elements, And A PLIB/FOV Folding Mirror Projects The Micro-Oscillated PLIB and FOV Towards Said Object, Whereby Said Linear CCD Image Detection Array Detects Time-Varying Speckle-Noise Patterns Produced By The Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object</u>

In Figs. 1I25F1 and 1I25F2, there is shown a PLIIM-based system of the present invention 915 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench 862 on opposite sides of the IFD module 861; and (iii) a 2-D PLIB micro-oscillation mechanism 916 arranged with each PLIM in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 916 comprises: a micro-oscillating cylindrical lens array structure 917 as shown in Figs. 1I4A through 1I4D for micro-oscillating the PLIB 918 laterally along its planar extent; a micro-oscillating PLIB/FOV reflection element 919 for micro-oscillating the PLIB and the field of view (FOV) 921 of the linear CCD image sensor (collectively 920) transversely along the direction orthogonal to the planar extent of the PLIB; and a stationary PLIB/FOV folding mirror 921 for jointing folding the micro-oscillated PLIB and the FOV towards the object to be illuminated and imaged in accordance with the

principles of the present invention. These optical components are configured together as an optical assembly as shown for the purpose of micro-oscillating the PLIB laterally along its planar extent while micro-oscillating both the PLIB and FOV of the linear CCD image sensor 863 transversely along the direction orthogonal thereto. During illumination operations, the PLIB transmitted from each PLIM 922 is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal thereto. This causes the phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A Phase-Only LCD-Based Phase Modulation Panel Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent And Produces Spatially Incoherent PLIB Components, A Stationary Cylindrical Lens Array Optically Combines And Projects Spatially Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Structure Micro-Oscillates The Spatially Incoherent PLIB Components Transversely Along The Direction Orthogonal To Said Planar Extent, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25G1 and 1I25G2, there is shown a PLIIM-based system of the present invention 925 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench 862 on opposite sides of the IFD module 861; and (iii) a 2-D PLIB micro-oscillation mechanism 926 arranged with each PLIM in an integrated manner.

As shown, 2-D PLIB micro-oscillation mechanism 926 comprises: a phase-only LCD phase modulation panel 927 for micro-oscillating PLIB 928 as shown in Figs. 1I8F and 1IG; a stationary cylindrical lens array 929; and a micro-PLIB reflection element 930. As shown in Fig. 1I25G2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB 928 is transmitted perpendicularly through phase modulation panel 927, whereas the FOV of the image detection array 863 is disposed at a small acute angle so that the PLIB and FOV converge on the micro-oscillating mirror element 930 so that the PLIB

and FOV (collectively 931) maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. These optical components are configured together as an optical assembly as shown for the purpose of micro-oscillating the PLIB laterally along its planar extent while micro-oscillating the PLIB transversely along the direction orthogonal thereto. During illumination operations, the PLIB transmitted from each PLIM is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal (i.e. transverse) thereto. This causes the phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A Multi-Faceted Cylindrical Lens Array Structure Rotating About Its Longitudinal Axis Within Each PLIM Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent And Produces Spatially Incoherent PLIB Components Therealong, A Stationary Cylindrical Lens Array Optically Combines And Projects The Spatially Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Structure Micro-Oscillates The Spatially Incoherent PLIB Components Transversely Along The Direction Orthogonal To Said Planar Extent, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25H1 and 1I25H2, there is shown a PLIIM-based system of the present invention 935 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 964 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A′ and 865B′ mounted on the optical bench 862 on opposite sides of the IFD module 861; and (iii) a 2-D PLIB micro-oscillation mechanism 936 arranged with each PLIM in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 936 comprises: a micro-oscillating multi-faceted cylindrical lens array structure 937 as shown in Figs. 1I12A and 1I12B, for micro-oscillating PLIB 938 produced therefrom along its planar extent as the cylindrical lens array structure 937 rotates about its axis of rotation; a stationary cylindrical lens array 939; and a micro-oscillating PLIB reflection element 940. As shown in Fig. 1I25H2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB is

transmitted perpendicularly through cylindrical lens array 939, whereas the FOV of the image detection array 863 is disposed at a small acute angle relative to the cylindrical lens array 939 so that the PLIB and FOV converge on the micro-oscillating mirror element 940 and the PLIB and FOV maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. As shown, these optical elements are configured together as an optical assembly as shown, for the purpose of micro-oscillating the PLIB laterally along its planar extent while micro-oscillating the PLIB transversely along the direction orthogonal thereto. During illumination operations, the PLIB 938 transmitted from each PLIM 865A′ and 865B′ is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal thereto, causing the phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

<u>PLIIM-Based System With An Integrated Speckle-Pattern Noise Reduction Subsystem, Wherein A Multi-Faceted Cylindrical Lens Array Structure Within Each PLIM Rotates About Its Longitudinal And Transverse Axes, Micro-Oscillates A Planar Laser Illumination Beam (PLIB) Laterally Along Its Planar Extent As Well As Transversely Along The Direction Orthogonal To Said Planar Extent, And Produces Spatially Incoherent PLIB Components Along Said Orthogonal Directions, And Wherein A Stationary Cylindrical Lens Array Optically Combines and Projects The Spatially Incoherent PLIB Components PLIB Onto The Same Points On The Surface Of An Object To Be Illuminated, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By the Spatial Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object</u>

In Figs. 1I25I1 through 1I25I3, there is shown a PLIIM-based system of the present invention 945 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench on opposite sides of the IFD module; and (iii) a 2-D PLIB micro-oscillation mechanism 946 arranged with each PLIM in an integrated manner.

As shown, the 2-D PLIB micro-oscillation mechanism 946 comprises: a micro-oscillating multi-faceted cylindrical lens array structure 947 as generally shown in Figs. 1I12A and 1I12B

(adapted for micro-oscillation about the optical axis of the VLD's laser illumination beam as well as along the planar extent of the PLIB); and a stationary cylindrical lens array 948. As shown in Figs. 1I25I2 and 1I25I3, the multi-faceted cylindrical lens array structure 947 is rotatably mounted within a housing portion 949, having a light transmission aperture 950 through which the PLIB exits, so that the structure 947 can rotate about its axis, while the housing portion 949 is micro-oscillated about an axis that is parallel with the optical axis of the focusing lens 15 within the PLIM 865A, 865B. Rotation of structure 947 can be achieved using an electrical motor with or without the use of a gearing mechanism, whereas micro-oscillation of the housing portion 949 can be achieved using any electro-mechanical device known in the art. As shown, these optical components are configured together as an optical assembly, for the purpose of micro-oscillating the PLIB 951 laterally along its planar extent while micro-oscillating the PLIB transversely along the direction orthogonal thereto. During illumination operations, the PLIB transmitted from each PLIM is spatial phase modulated along the planar extent thereof as well as along the direction orthogonal thereto. This causes the phase along the wavefront of each transmitted PLIB to be modulated in two orthogonal dimensions and numerous substantially different time-varying speckle-noise patterns to be produced at the vertically-elongated image detection elements 863 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated "Hybrid-Type" Speckle-Pattern Noise Reduction Subsystem, Wherein A High-Speed Temporal Intensity Modulation Panel Temporal Intensity Modulates A Planar Laser Illumination Beam (PLIB) To Produce Temporally Incoherent PLIB Components Along Its Planar Extent, A Stationary Cylindrical Lens Array Optically Combines and Projects The Temporally Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Element Micro-Oscillates The PLIB Transversely Along The Direction Orthogonal To Said Planar Extent To Produce Spatially Incoherent PLIB Components Along Said Transverse Direction, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Temporally And Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25J1 and 1I25J2, there is shown a PLIIM-based system of the present invention 955 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench on

opposite sides of the IFD module; and (iii) a hybrid-type PLIB modulation mechanism 956 arranged with each PLIM.

As shown, PLIB modulation mechanism 955 comprises: a temporal intensity modulation panel (i.e. high-speed optical shutter) 957 as shown in Figs. 1I14A and 1I14B; a stationary cylindrical lens array 958; and a micro-oscillating PLIB reflection element 959. As shown in Fig. 1I25J2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB 960 is transmitted perpendicularly through temporal intensity modulation panel 957, whereas the FOV of the image detection array 863 is disposed at a small acute angle relative to PLIB 960 so that the PLIB and FOV (collectively 961) converge on the micro-oscillating mirror element 959 and the PLIB and FOV maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. As shown, these optical elements are configured together as an optical assembly, for the purpose of temporal intensity modulating the PLIB 960 uniformly along its planar extent while micro-oscillating PLIB 960 transversely along the direction orthogonal thereto. During illumination operations, the PLIB transmitted from each PLIM is temporal intensity modulated along the planar extent thereof and spatial phase modulated during micro-oscillation along the direction orthogonal thereto, thereby producing numerous substantially different time-varying speckle-noise patterns at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

<u>PLIIM-Based System With An Integrated "Hybrid-Type" Speckle-Pattern Noise Reduction Subsystem, Wherein An Optically-Reflective Cavity Externally Attached To Each VLD In The System Temporal Phase Modulates A Planar Laser Illumination Beam (PLIB) To Produce Temporally Incoherent PLIB Components Along Its Planar Extent, A Stationary Cylindrical Lens Array Optically Combines And Projects The Temporally Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Element Micro-Oscillates The PLIB Transversely Along The Direction Orthogonal To Said Planar Extent To Produce Spatially Incoherent PLIB Components Along Said Transverse Direction, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Temporally and Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object</u>

In Figs. 1I25K1 and 1I25K2, there is shown a PLIIM-based system of the present invention 965 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection

elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A″ and 865B″ mounted on the optical bench 862 on opposite sides of the IFD module 861; and (iii) a hybrid-type PLIB modulation mechanism 966 arranged with each PLIM.

As shown, PLIB modulation mechanism 966 comprises an optically-reflective cavity (i.e. etalon) 967 attached external to each VLD 13 as shown in Figs. 1I17A and 1I17B; a stationary cylindrical lens array 968; and a micro-oscillating PLIB reflection element 969. As shown, these optical components are configured together as an optical assembly, for the purpose of temporal intensity modulating the PLIB 970 uniformly along its planar extent while micro-oscillating the PLIB transversely along the direction orthogonal thereto. As shown in Fig. 1I25K2, each PLIM 865A″ and 865B″ is pitched slightly relative to the optical axis of the IFD module 961 so that the PLIB 970 is transmitted perpendicularly through cylindrical lens array 968, whereas the FOV of the image detection array 863 is disposed at a small acute angle so that the PLIB and FOV converge on the micro-oscillating mirror element 968 so that the PLIB and FOV (collectively 971) maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. During illumination operations, the PLIB transmitted from each PLIM is temporal phase modulated along the planar extent thereof and spatial phase modulated during micro-oscillation along the direction orthogonal thereto, thereby producing numerous substantially different time-varying speckle-noise patterns at the vertically-elongated image detection elements of the IFD Subsystem during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

<u>PLIIM-Based System With An Integrated "Hybrid-Type" Speckle-Pattern Noise Reduction Subsystem, Wherein Each Visible Mode Locked Laser Diode (MLLD) Employed In The PLIM of The System Generates A High-Speed Pulsed (i.e. Temporal Intensity Modulated) Planar Laser Illumination Beam (PLIB) Having Temporally Incoherent PLIB Components Along Its Planar Extent, A Stationary Cylindrical Lens Array Optically Combines And Projects The Temporally Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Element Micro-Oscillates PLIB Transversely Along The Direction Orthogonal To Said Planar Extent To Produce Spatially Incoherent PLIB Components Along Said Transverse Direction, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Temporally And Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object</u>

In Figs. 1I25L1 and 1I25L2, there is shown a PLIIM-based system of the present invention 975 having speckle-pattern noise reduction capabilities embodied therein, which

comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench on opposite sides of the IFD module; and (iii) a hybrid-type PLIB modulation mechanism 976 arranged with each PLIM in an integrated manner.

As shown, the PLIB modulation mechanism 976 comprises: a visible mode-locked laser diode (MLLD) 977 as shown in Figs. 1I15A and 1I15D; a stationary cylindrical lens array 978; and a micro-oscillating PLIB reflection element 979. As shown in Fig. 1I25L2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB 980 is transmitted perpendicularly through cylindrical lens array 978, whereas the FOV of the image detection array 863 is disposed at a small acute angle, relative to PLIB 980, so that the PLIB and FOV converge on the micro-oscillating mirror element 868 so that the PLIB and FOV (collectively 981) maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. As shown, these optical components are configured together as an optical assembly, for the purpose of producing a temporal intensity modulated PLIB while micro-oscillating the PLIB transversely along the direction orthogonal to its planar extent. During illumination operations, the PLIB transmitted from each PLIM is temporal intensity modulated along the planar extent thereof and spatial phase modulated during micro-oscillation along the direction orthogonal thereto, thereby producing numerous substantially different time-varying speckle-noise patterns at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated "Hybrid-Type" Speckle-Pattern Noise Reduction Subsystem, Wherein The Visible Laser Diode (VLD) Employed In Each PLIM Of The System Is Continually Operated In A Frequency-Hopping Mode So As To Temporal Frequency Modulate The Planar Laser Illumination Beam (PLIB) And Produce Temporally Incoherent PLIB Components Along Its Planar Extent, A Stationary Cylindrical Lens Array Optically Combines And Projects The Temporally Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflecting Element Micro-Oscillates The PLIB Transversely Along The Direction Orthogonal To Said Planar Extent And Produces Spatially Incoherent PLIB Components Along Said Transverse Direction, And A Linear (1D) CCD Image Detection Array With Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Temporally And Spatial Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25M1 and 1I25M2, there is shown a PLIIM-based system of the present invention 985 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench on opposite sides of the IFD module; and (iii) a hybrid-type PLIB modulation mechanism 986 arranged with each PLIM in an integrated manner.

As shown, PLIB modulation mechanism 986 comprises: a visible laser diode (VLD) 13 continuously driven into a high-speed frequency hopping mode (as shown in Figs. 1I16A and 1I15B); a stationary cylindrical lens array 986; and a micro-oscillating PLIB reflection element 987. As shown in Fig. 1I25M2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB 988 is transmitted perpendicularly through cylindrical lens array 986, whereas the FOV of the image detection array 863 is disposed at a small acute angle, relative to PLIB 988, so that the PLIB and FOV (collectively 988) converge on the micro-oscillating mirror element 987 so that the PLIB and FOV maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. As shown, these optical components are configured together as an optical assembly as shown, for the purpose of producing a temporal frequency modulated PLIB while micro-oscillating the PLIB transversely along the direction orthogonal to its planar extent. During illumination operations, the PLIB transmitted from each PLIM is temporal frequency modulated along the planar extent thereof and spatial intensity modulated during micro-oscillation along the direction orthogonal thereto, thereby producing numerous substantially different time-varying speckle-noise patterns at the vertically-elongated image detection elements 864 during the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-

integration time period of the image detection array 863, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array.

PLIIM-Based System With An Integrated "Hybrid-Type" Speckle-Pattern Noise Reduction Subsystem, Wherein A Pair of Micro-Oscillating Spatial Intensity Modulation Panels Spatial Intensity Modulate A Planar Laser Illumination Beam (PLIB) And Produce Spatially Incoherent PLIB Components Along Its Planar Extent, A Stationary Cylindrical Lens Array Optically Combines And Projects The Spatially Incoherent PLIB Components Onto The Same Points On The Surface Of An Object To Be Illuminated, And Wherein A Micro-Oscillating Light Reflective Structure Micro-Oscillates Said PLIB Transversely Along The Direction Orthogonal To Said Planar Extent And Produces Spatially Incoherent PLIB Components Along Said Transverse Direction, And A Linear (1D) CCD Image Detection Array Having Vertically-Elongated Image Detection Elements Detects Time-Varying Speckle-Noise Patterns Produced By The Spatially Incoherent PLIB Components Reflected/Scattered Off The Illuminated Object

In Figs. 1I25N1 and 1I25N2, there is shown a PLIIM-based system of the present invention 995 having speckle-pattern noise reduction capabilities embodied therein, which comprises: (i) an image formation and detection (IFD) module 861 mounted on an optical bench 862 and having a linear (1D) CCD image sensor 863 with vertically-elongated image detection elements 864 characterized by a large height-to-width (H/W) aspect ratio; (ii) a PLIA comprising a pair of planar laser illumination modules (PLIMs) 865A and 865B mounted on the optical bench on opposite sides of the IFD module; and (iii) a hybrid-type PLIB modulation mechanism 996 arranged with each PLIM in an integrated manner.

As shown, the PLIB modulation mechanism 996 comprises a micro-oscillating spatial intensity modulation array 997 as shown in Figs. 1I221A through 1I21D; a stationary cylindrical lens array 998; and a micro-oscillating PLIB reflection element 999. As shown in Fig. 1I25N2, each PLIM 865A and 865B is pitched slightly relative to the optical axis of the IFD module 861 so that the PLIB 1000 is transmitted perpendicularly through cylindrical lens array 998, whereas the FOV of the image detection array 863 is disposed at a small acute angle, relative to PLIB 1000, so that the PLIB and FOV (collectively 1001) converge on the micro-oscillating mirror element 999 so that the PLIB and FOV maintain a coplanar relationship as they are jointly micro-oscillated in planar and orthogonal directions during object illumination operations. As shown, these optical components are configured together as an optical assembly, for the purpose of producing a spatial intensity modulated PLIB while micro-oscillating the PLIB transversely along the direction orthogonal to its planar extent. During illumination operations, the PLIB transmitted from each PLIM is spatial intensity modulated along the planar extent thereof and spatial phase modulated during micro-oscillation along the direction orthogonal thereto, thereby producing numerous substantially different time-varying speckle-noise patterns at the vertically-elongated image detection elements of the IFD Subsystem during

the photo-integration time period thereof. These numerous time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array, thereby reducing the RMS power level of speckle-noise patterns observed at the image detection array;

Notably, in this embodiment, it may be preferred that the cylindrical lens array 998 may be realized using light diffractive optical materials so that each spectral component within the transmitted PLIB 1001 will be diffracted at slightly different angles dependent on its optical wavelength. For example, using this technique, the PLIB 1000 can be made to undergo micro-movement along the transverse direction (or planar extent of the PLIB) during target illumination operations. Therefore, such wavelength-dependent PLIB movement can be used to modulate the spatial phase of the PLIB wavefront along directions extending either within the plane of the PLIB or along a direction orthogonal thereto, depending on how the diffractive-type cylindrical lens array is designed. In such applications, both temporal frequency modulation as well as spatial phase modulation of the PLIB wavefront would occur, thereby creating a hybrid-type despeckling scheme.

Advantages of Using Linear Image Detection Arrays Having Vertically-Elongated Image Detection Elements

If the heights of the PLIB and the FOV of the linear image detection array are comparable in size in a PLIIM-based system, then only a slight misalignment of the PLIB and the FOV is required to displace the PLIB from the FOV, rendering a dark image at the image detector in the PLIIM-based system. To use this PLIB/FOV alignment technique successfully, the mechanical parts required for positioning the CCD linear image sensor and the VLDs of the PLIA must be extremely rugged in construction, which implies additional size, weight, and cost of manufacture.

The PLIB/FOV misalignment problem described above can be solved using the PLIIM-based imaging engine design shown in Figs. 1I25A2 through 1I25N2. In this novel design, the linear image detector 863 with its vertically-elongated image detection elements 864 is used in conjunction with a PLIB having a height that is substantially smaller than the height dimension of the magnified field of view (FOV) of each image detection element in the linear image detector 863. This condition between the PLIB and the FOV reduces the tolerance on the degree of alignment that must be maintained between the FOV of the linear image sensor and the plane of the PLIB during planar laser illumination and imaging operations. It also avoids the need to increase the output power of the VLDs in the PLIA, which might either cause problems from a safety and laser class standpoint, or require the use of more powerful VLDs which are

expensive to procure and require larger heat sinks to operate properly. Thus, using the PLIIM-based imaging engine design shown in Figs. 1I25A2 through 1I25N2, the PLIB and FOV thereof can move slightly with respect to each other during system operation without "loosing alignment" because the FOV of the image detection elements spatially encompasses the entire PLIB, while providing significant spatial tolerances on either side of the PLIB. By the term "alignment", it is understood that the FOV of the image detection array and the principal plane of the PLIB sufficiently overlap over the entire width and depth of object space (i.e. working distance) such that the image obtained is bright enough to be useful in whatever application at hand (e.g. bar code decoding, OCR software processing, etc.).

A notable advantage derived when using this PLIB/FOV alignment method is that no sacrifice in laser intensity is required. In fact, because the FOV is guaranteed to receive all of the laser light from the illuminating PLIB, whether stationary or moving relative to the target object, the total output power of the PLIB may be reduced if necessary or desired in particular applications.

In the illustrative embodiments described above, each PLIIM-based system is provided with an integrated despeckling mechanism, although it is clearly understood that the PLIB/FOV alignment method described above can be practiced with or without such despeckling techniques.

In a first illustrative embodiment, the PLIB/FOV alignment method may be practiced using a linear CCD image detection array (i.e. sensor) with, for example, 10 micron tall image detection elements (i.e. pixels) and image forming optics having a magnification factor of say, for example, 15X. In this first illustrative embodiment, the height of the FOV of the image detection elements on the target object would be about 150 microns. In order for the height of the PLIB to be significantly smaller than this FOV height dimension, e.g. by a factor of five, the height of the PLIB would have to be focused to about 30 microns.

In a second alternative embodiment, using a linear CCD image detector with image detection elements having a 200 micron height dimension and equivalent optics (having a magnification factor 15X), the height dimension for the FOV would be 3000 microns. In this second alternative embodiment, a PLIB focused to 750 microns (rather than 30 microns in the first illustrative embodiment above) would provide the same amount of return signal at the linear image detector, but with angular tolerances which are almost 20 times as large as those obtained in the first illustrative embodiment. In view of the fact that it can be quite difficult to focus a planarized laser beam to a few microns thickness over an extended depth of field, the second illustrative embodiment would be preferred over the first illustrative embodiment.

In view of the fact that linear CCD image detectors with 200 micron tall image detection elements are generally commercially available in lengths of only one or two thousand image

detection elements (i.e. pixels), the PLIB/FOV alignment method described above would be best applicable to PLIIM-based hand-held imaging applications as illustrated, for example, in Figs. 1I25A2 through 1I25N2. In view of the fact that most industrial-type imaging systems require linear image sensors having six to eight thousand image detection elements, the PLIB/FOV alignment method illustrated in Fig. 1B3 would be best applicable to PLIIM-based conveyor-mounted/industrial imaging systems as illustrated, for example, in Figs. 9 through 32A. Depending on the optical path lengths required in the PLIIM-based POS imaging systems shown in Figs. 33A through 34C, either of these PLIB/FOV alignment methods may be used with excellent results.

Second Alternative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 1A

In Fig. 1Q1, the second illustrative embodiment of the PLIIM-based system of Fig. 1A, indicated by reference numeral 1B, is shown comprising: a 1-D type image formation and detection (IFD) module 3′, as shown in Fig. 1B1; and a pair of planar laser illumination arrays 6A and 6B . As shown, these arrays 6A and 6B are arranged in relation to the image formation and detection module 3 so that the field of view thereof is oriented in a direction that is coplanar with the planes of laser illumination produced by the planar illumination arrays, without using any laser beam or field of view folding mirrors. One primary advantage of this system architecture is that it does not require any laser beam or FOV folding mirrors, employs the few optical surfaces, and maximizes the return of laser light, and is easy to align. However, it is expected that this system design will most likely require a system housing having a height dimension which is greater than the height dimension required by the system design shown in Fig. 1B1.

As shown in Fig. 1Q2, PLIIM-based system of Fig. 1Q1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3 having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array

(e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM-based system of Figs 1P1 and 1O2 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

<u>Third Alternative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 1A</u>

In Fig. 1R1, the third illustrative embodiment of the PLIIM-based system of Figs. 1A, indicated by reference numeral 1C, is shown comprising: a 1-D type image formation and detection (IFD) module 3 having a field of view (FOV), as shown in Fig. 1B1; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; and a pair of planar laser beam folding mirrors 37A and 37B arranged. The function of the planar laser illumination beam folding mirrors 37A and 37B is to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 37A and 37B such that the field of view (FOV) of the image formation and detection module 3 is aligned in a direction that is coplanar with the planes of first and second planar laser illumination beams during object illumination and imaging operations. One notable disadvantage of this system architecture is that it requires additional optical surfaces which can reduce the intensity of outgoing laser illumination and therefore reduce slightly the intensity of returned laser illumination reflected off target objects. Also this system design requires a more complicated beam/FOV adjustment scheme. This system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. In this system embodiment, the PLIMs are mounted on the optical bench as far back as possible from the beam folding mirrors, and cylindrical lenses with larger radiuses will be employed in the design of each PLIM.

As shown in Fig. 1R2, PLIIM-based system 1C shown in Fig. 1R1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules (PLIMs) 6A, 6B, and each PLIM being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; pair of planar laser beam folding mirrors 37A and 37B arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM system of Figs 1Q1 and 1Q2 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

Fourth Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 1A

In Fig. 1S1, the fourth illustrative embodiment of the PLIIM-based system of Figs. 1A, indicated by reference numeral 1D, is shown comprising: a 1-D type image formation and detection (IFD) module 3 having a field of view (FOV), as shown in Fig. 1B1; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; a field of view folding mirror 9 for folding the field of view (FOV) of the image formation and detection module 3 about 90 degrees downwardly; and a pair of planar laser

beam folding mirrors 37A and 37B arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B such that the planes of first and second planar laser illumination beams 7A and 7B are in a direction that is coplanar with the field of view of the image formation and detection module 3. Despite inheriting most of the disadvantages associated with the system designs shown in Figs. 1B1 and 1R1, this system architecture allows the length of the system housing to be easily minimized, at the expense of an increase in the height and width dimensions of the system housing.

As shown in Fig. 1S2, PLIIM-based system 1D shown in Fig. 1S1 comprises: planar laser illumination arrays (PLIAs) 6A and 6B, each having a plurality of planar laser illumination modules (PLIMs) 11A through 11F, and each PLIM being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3 having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; a field of view folding mirror 9 for folding the field of view (FOV) of the image formation and detection module 3; a pair of planar laser beam folding mirrors 9 and 3 arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 37A and 37B; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM-based system of Figs 1S1 and 1S2 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

<u>Applications For The First Generalized Embodiment Of The PLIIM-Based System Of The Present Invention, and the Illustrative Embodiments Thereof</u>

Fixed focal distance type PLIIM-based systems shown in Figs. 1B1 through 1U are ideal for applications in which there is little variation in the object distance, such as in a conveyor-type bottom scanner applications. As such scanning systems employ a fixed focal length imaging lens, the image resolution requirements of such applications must be examined carefully to determine that the image resolution obtained is suitable for the intended application. Because the object distance is approximately constant for a bottom scanner application (i.e. the bar code almost always is illuminated and imaged within the same object plane), the dpi resolution of acquired images will be approximately constant. As image resolution is not a concern in this type of scanning applications, variable focal length (zoom) control is unnecessary, and a fixed focal length imaging lens should suffice and enable good results.

A fixed focal distance PLIIM system generally takes up less space than a variable or dynamic focus model because more advanced focusing methods require more complicated optics and electronics, and additional components such as motors. For this reason, fixed focus PLIIM-based systems are good choices for handheld and presentation scanners as indicated in Fig. 1U, wherein space and weight are always critical characteristics. In these applications, however, the object distance can vary over a range from several to a twelve or more inches, and so the designer must exercise care to ensure that the scanner's depth of field (DOF) alone will be sufficient to accommodate all possible variations in target object distance and orientation. Also, because a fixed focus imaging subsystem implies a fixed focal length camera lens, the variation in object distance implies that the dots per inch resolution of the image will vary as well. The focal length of the imaging lens must be chosen so that the angular width of the field of view (FOV) is narrow enough that the dpi image resolution will not fall below the minimum acceptable value anywhere within the range of object distances supported by the PLIIM-based system.

<u>Second Generalized Embodiment Of The Planar Laser Illumination And Electronic Imaging System Of The Present Invention</u>

The second generalized embodiment of the PLIIM-based system of the present invention 11 is illustrated in Figs. 1V1 and 1V3. As shown in Fig. 1V1, the PLIIM-based system 1' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3'; and a pair of planar laser illumination arrays (PLIAs)

6A and 6B mounted on opposite sides of the IFD module 3'. During system operation, laser illumination arrays 6A and 6B each produce a planar beam of laser illumination 12' which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the image formation and detection module 3', so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 3-D scanning region.

As shown in Figs. 1V2 and 1V3, the PLIIM-based system of Fig. 1V1 comprises: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and a 1-D image detection array 3 (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; a field of view sweeping mirror 9 operably connected to a motor mechanism 38 under control of camera control computer 22, for folding and sweeping the field of view of the image formation and detection module 3; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams (PLIBs) 7A and 7B, wherein each VLD 11 is driven by a VLD drive circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; a pair of planar laser illumination beam folding/sweeping mirrors 37A and 37B operably connected to motor mechanisms 39A and 39B, respectively, under control of camera control computer 22, for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

An image formation and detection (IFD) module 3 having an imaging lens with a fixed focal length has a constant angular field of view (FOV); that is, the farther the target object is located from the IFD module, the larger the projection dimensions of the imaging subsystem's

FOV become on the surface of the target object. A disadvantage to this type of imaging lens is that the resolution of the image that is acquired, in terms of pixels or dots per inch, varies as a function of the distance from the target object to the imaging lens. However, a fixed focal length imaging lens is easier and less expensive to design and produce than the alternative, a zoom-type imaging lens which will be discussed in detail hereinbelow with reference to Figs. 3A through 3J4.

Each planar laser illumination module 6A through 6B in PLIIM-based system 1' is driven by a VLD driver circuit 18 under the camera control computer 22. Notably, laser illumination beam folding/sweeping mirror 37A' and 38B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 38, 39A, and 39B, respectively, operated under the control of the camera control computer 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which is synchronously controlled to enable the planar laser illumination beams 7A, 7B and FOV 10 to move together in a spatially-coplanar manner during illumination and detection operations within the PLIIM-based system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3, the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3 and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A' and 6B', beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3 and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM-based system embodiment 1' employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

Applications For The Second Generalized Embodiment Of The PLIIM System Of The Present Invention

The fixed focal length PLIIM-based system shown in Figs. 1V1-1V3 has a 3-D fixed field of view which, while spatially-aligned with a composite planar laser illumination beam 12 in a coplanar manner, is automatically swept over a 3-D scanning region within which bar code symbols and other graphical indicia 4 may be illuminated and imaged in accordance with the principles of the present invention. As such, this generalized embodiment of the present invention is ideally suited for use in hand-supportable and hands-free presentation type bar code symbol readers shown in Figs. 1V4 and 1V5, respectively, in which rasterlike-scanning (i.e. up and down) patterns can be used for reading 1-D as well as 2-D bar code symbologies such as the PDF 147 symbology. In general, the PLIIM-based system of this generalized embodiment may have any of the housing form factors disclosed and described in Applicants' copending US Application Nos. 09/204,176 entitled filed December 3, 1998 and 09/452,976 filed December 2, 1999, and WIPO Publication No. WO 00/33239 published June 8, 2000, incorporated herein by reference. The beam sweeping technology disclosed in copending Application No. 08/931,691 filed September 16, 1997, incorporated herein by reference, can be used to uniformly sweep both the planar laser illumination beam and linear FOV in a coplanar manner during illumination and imaging operations.

Third Generalized Embodiment Of The PLIIM-Based System Of The Present Invention

The third generalized embodiment of the PLIIM-based system of the present invention 40 is illustrated in Fig. 2A. As shown therein, the PLIIM system 40 comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3' including a 1-D electronic image detection array 3A, a linear (1-D) imaging subsystem (LIS) 3B' having a fixed focal length, a variable focal distance, and a fixed field of view (FOV), for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B , each mounted on opposite sides of the IFD module 3', such that each planar laser illumination array 6A and 6B produces a composite plane of laser beam illumination 12 which is disposed substantially coplanar with the field view of the image formation and detection module 3' during object illumination and image detection operations carried out by the PLIIM-based system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3', and any non-moving FOV and/or planar laser illumination beam folding mirrors employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3' and any stationary FOV folding mirrors employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and any planar laser illumination beam folding mirrors employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM-based system embodiment 40 employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM-based system will be described below.

An image formation and detection (IFD) module 3 having an imaging lens with variable focal distance, as employed in the PLIIM-based system of Fig. 2A, can adjust its image distance to compensate for a change in the target's object distance; thus, at least some of the component lens elements in the imaging subsystem are movable, and the depth of field of the imaging subsystems does not limit the ability of the imaging subsystem to accommodate possible object distances and orientations. A variable focus imaging subsystem is able to move its components in such a way as to change the image distance of the imaging lens to compensate for a change in the target's object distance, thus preserving good focus no matter where the target object might be located. Variable focus can be accomplished in several ways, namely: by moving lens elements; moving imager detector/sensor; and dynamic focus. Each of these different methods will be summarized below for sake of convenience.

Use Of Moving Lens Elements In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM-based system embodiment can employ an imaging lens which is made up of several component lenses contained in a common lens barrel. A variable focus type imaging lens such as this can move one or more of its lens elements in order to change the effective distance between the lens and the image sensor, which remains stationary. This change in the image distance compensates for a change in the object distance of the target object and keeps the return light in focus. The position at which the focusing lens element(s) must be in order to image light returning from a target object at a given

object distance is determined by consulting a lookup table, which must be constructed ahead of time, either experimentally or by design software, well known in the optics art.

Use Of An Moving Image Detection Array In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM-based system embodiment can be constructed so that all the lens elements remain stationary, with the imaging detector/sensor array being movable relative to the imaging lens so as to change the image distance of the imaging subsystem. The position at which the image detector/sensor must be located to image light returning from a target at a given object distance is determined by consulting a lookup table, which must be constructed ahead of time, either experimentally or by design software, well known in the art.

Use Of Dynamic Focal Distance Control In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM-based system embodiment can be designed to embody a "dynamic" form of variable focal distance (i.e. focus) control, which is an advanced form of variable focus control. In conventional variable focus control schemes, one focus (i.e. focal distance) setting is established in anticipation of a given target object. The object is imaged using that setting, then another setting is selected for the next object image, if necessary. However, depending on the shape and orientation of the target object, a single target object may exhibit enough variation in its distance from the imaging lens to make it impossible for a single focus setting to acquire a sharp image of the entire object. In this case, the imaging subsystem must change its focus setting while the object is being imaged. This adjustment does not have to be made continuously; rather, a few discrete focus settings will generally be sufficient. The exact number will depend on the shape and orientation of the package being imaged and the depth of field of the imaging subsystem used in the IFD module.

It should be noted that dynamic focus control is only used with a linear image detection/sensor array, as used in the system embodiments shown in Figs. 2A through 3J4. The reason for this limitation is quite clear: an area-type image detection array captures an entire image after a rapid number of exposures to the planar laser illumination beam, and although changing the focus setting of the imaging subsystem might clear up the image in one part of the detector array, it would induce blurring in another region of the image, thus failing to improve the overall quality of the acquired image.

FirstIllustrative Embodiment Of The PLIIM-Based System Shown In Fig. 2A

The first illustrative embodiment of the PLIIM-based system of Fig. 2A, indicated by reference numeral 40A, is shown in Fig. 2B1. As illustrated therein, the field of view of the image formation and detection module 3' and the first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations.

The PLIIM-based system illustrated in Fig. 2B1 is shown in greater detail in Fig. 2B2. As shown therein, the linear image formation and detection module 3' is shown comprising an imaging subsystem 3B', and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images (e.g. 6000 pixels, at a 60MHZ scanning rate) formed thereon by the imaging subsystem 3B', providing an image resolution of 200dpi or 8 pixels/mm, as the image resolution that results from a fixed focal length imaging lens is the function of the object distance (i.e. the longer the object distance, the lower the resolution). The imaging subsystem 3B' has a fixed focal length imaging lens (e.g. 80mm Pentax lens, F4.5), a fixed field of view (FOV), and a variable focal distance imaging capability (e.g. 36" total scanning range), and an auto-focusing image plane with a response time of about 20-30 milliseconds over about 5mm working range.

As shown, each planar laser illumination array (PLIA) 6A, 6B comprises a plurality of planar laser illumination modules (PLIMs) 11A through 11F, closely arranged relative to each other, in a rectilinear fashion. As taught hereinabove, the relative spacing and orientation of each PLIM 11 is such that the spatial intensity distribution of the individual planar laser beams 7A, 7B superimpose and additively produce composite planar laser illumination beam 12 having a substantially uniform power density distribution along the widthwise dimensions of the laser illumination beam, throughout the entire working range of the PLIIM-based system.

As shown in Fig. 2C1, the PLIIM system of Fig. 2B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and

detection module 3A; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2C2 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM-based system of Fig. 2B1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 30 contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3B' mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with an optical element translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 2A

The second illustrative embodiment of the PLIIM-based system of Fig. 2A, indicated by reference numeral 40B, is shown in Fig. 2D1 as comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A

realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; and a pair of planar laser illumination arrays 6A and 6B arranged in relation to the image formation and detection module 3' such that the field of view thereof folded by the field of view folding mirror 9 is oriented in a direction that is coplanar with the composite plane of laser illumination 12 produced by the planar illumination arrays, during object illumination and image detection operations, without using any laser beam folding mirrors.

One primary advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to be installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3' can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to be practiced in a relatively easy manner.

As shown in Fig. 2D2, the PLIIM-based system of Fig. 2D1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3', for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2D2 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM-based system of Fig. 2D1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A' mounted along the optical bench before the image detecting array 3A', and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with a translator 3E, in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

<u>Third Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 2A</u>

The second illustrative embodiment of the PLIIM-based system of Fig. 2A, indicated by reference numeral 40C, is shown in Fig. 2D1 as comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A, 7B, and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the field of view of the image formation and detection during object illumination and image detection operations.

The primary disadvantage of this system architecture is that it requires additional optical surfaces (i.e. the planar laser beam folding mirrors) which reduce outgoing laser light

and therefore the return laser light slightly. Also this embodiment requires a complicated beam/FOV adjustment scheme. Thus, this system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. Notably, in this system embodiment, the PLIMs are mounted on the optical bench 8 as far back as possible from the beam folding mirrors 37A, 37B, and cylindrical lenses 16 with larger radiuses will be employed in the design of each PLIM 11.

As shown in Fig. 2E2, the PLIIM-based system of Fig. 2E1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2E3 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM-based system of Fig. 2E1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by

moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

<u>Fourth Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 2A</u>

The fourth illustrative embodiment of the PLIIM-based system of Fig. 2A, indicated by reference numeral 40D, is shown in Fig. 2F1 as comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding mirror 9 for folding the FOV of the imaging subsystem 3B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; and a pair of planar laser beam folding mirrors 37A and 37B arranged in relation to the planar laser illumination arrays 6A and 6B so as to fold the optical paths of the first and second planar laser illumination beams 7A, 7B in a direction that is coplanar with the folded FOV of the image formation and detection module 3', during object illumination and image detection operations.

As shown in Fig. 2F2, the PLIIM system 40D of Fig. 2F1 further comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11B, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image

data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2F3 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM-based system of Fig. 2F1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench 3D before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Third Generalized Embodiment Of The PLIIM-Based System Of The Present Invention, and the Illustrative Embodiments Thereof

As the PLIIM-based systems shown in Figs. 2A through 2F3 employ an IFD module 3' having a linear image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, such PLIIM-based systems are good candidates for use in a conveyor top scanner application, as shown in Figs. 2G, as the variation in target object distance can be up to a meter or more (from the imaging subsystem). In general, such object distances are too great a range for the depth of field (DOF) characteristics of the imaging subsystem alone to accommodate such object distance parameter variations during object illumination and imaging

operations. Provision for variable focal distance control is generally sufficient for the conveyor top scanner application shown in Fig. 2G, as the demands on the depth of field and variable focus or dynamic focus control characteristics of such PLIIM-based system are not as severe in the conveyor top scanner application, as they might be in the conveyor side scanner application, also illustrated in Fig. 2G.

Notably, by adding dynamic focusing functionality to the imaging subsystem of any of the embodiments shown in Figs. 2A through 2F3, the resulting PLIIM-based system becomes appropriate for the conveyor side-scanning application discussed above, where the demands on the depth of field and variable focus or dynamic focus requirements are greater compared to a conveyor top scanner application.

Fourth Generalized Embodiment Of The PLIIM System Of The Present Invention

The fourth generalized embodiment of the PLIIM-based system 40' of the present invention is illustrated in Figs. 2I1 and 2I2. As shown in Fig. 2I1, the PLIIM-based system 40' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3'; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3'. During system operation, laser illumination arrays 6A and 6B each produce a moving planar laser illumination beam 12' which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the image formation and detection module 3', so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 3-D scanning region.

As shown in Figs. 2I2 and 2I3, the PLIIM-based system of Fig. 2I1 comprises: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding and sweeping mirror 9' for folding and sweeping the field of view 10 of the image formation and detection module 3'; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B, wherein each VLD 11 is driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB

components onto points along the surface of the object being illuminated; a pair of planar laser illumination beam sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. As shown in Fig. 2F2, each planar laser illumination module 11A through 11F, is driven by a VLD driver circuit 18 under the camera control computer 22. Notably, laser illumination beam folding/sweeping mirrors 37A' and 37B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 39A, 39B, 38, respectively, operated under the control of the camera control computer 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which are synchronously controlled to enable the composite planar laser illumination beam and FOV to move together in a spatially-coplanar manner during illumination and detection operations within the PLIIM system.

Fig. 2I4 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM-based system of Fig. 2I1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with a translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while

the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3', the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3' and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM-based system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B , beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3' and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment 40' employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

Applications For The Fourth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention

As the PLIIM-based systems shown in Figs. 2I1 through 2I4 employ (i) an IFD module having a linear image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, and (ii) a mechanism for automatically sweeping both the planar (2-D) FOV and planar laser illumination beam through a 3-D scanning field in an "up and down" pattern while maintaining the inventive principle of "laser-beam/FOV coplanarity" disclosed herein, such PLIIM-based systems are good candidates for use in a hand-held scanner application, shown in Figs. 2I5, and the hands-free presentation scanner application illustrated in Fig. 2I6. The provision of variable focal distance control in these illustrative PLIIM-based systems is most sufficient for the hand-held scanner application shown in Fig. 2I5, and presentation scanner application shown in Figs. 2I6, as the demands placed on the depth of field and variable focus control characteristics of such systems will not be severe.

Fifth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention

The fifth generalized embodiment of the PLIIM-based system of the present invention, indicated by reference numeral 50, is illustrated in Fig. 3A. As shown therein, the PLIIM system 50 comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3" including a 1-D electronic image detection array 3A, a linear (1-D) imaging subsystem (LIS) 3B" having a variable focal length, a variable focal distance, and a variable field of view (FOV), for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 3", such that each planar laser illumination array 6A and 6B produces a plane of laser beam illumination 7A, 7B which is disposed substantially coplanar with the field view of the image formation and detection module 3" during object illumination and image detection operations carried out by the PLIIM-based system.

In the PLIIM-based system of Fig. 3A, the linear image formation and detection (IFD) module 3" has an imaging lens with a variable focal length (i.e. a zoom-type imaging lens) 3B1, that has a variable angular field of view (FOV); that is, the farther the target object is located from the IFD module, the larger the projection dimensions of the imaging subsystem's FOV become on the surface of the target object. A zoom imaging lens is capable of changing its focal length, and therefore its angular field of view (FOV) by moving one or more of its component lens elements. The position at which the zooming lens element(s) must be in order to achieve a given focal length is determined by consulting a lookup table, which must be constructed ahead of time either experimentally or by design software, in a manner well known in the art. An advantage to using a zoom lens is that the resolution of the image that is acquired, in terms of pixels or dots per inch, remains constant no matter what the distance from the target object to the lens. However, a zoom camera lens is more difficult and more expensive to design and produce than the alternative, a fixed focal length camera lens.

The image formation and detection (IFD) module 3" in the PLIIM-based system of Fig. 3A also has an imaging lens 3B2 with variable focal distance, which can adjust its image distance to compensate for a change in the target's object distance. Thus, at least some of the component lens elements in the imaging subsystem 3B2 are movable, and the depth of field (DOF) of the imaging subsystem does not limit the ability of the imaging subsystem to

accommodate possible object distances and orientations. This variable focus imaging subsystem 3B2 is able to move its components in such a way as to change the image distance of the imaging lens to compensate for a change in the target's object distance, thus preserving good image focus no matter where the target object might be located. This variable focus technique can be practiced in several different ways, namely: by moving lens elements in the imaging subsystem; by moving the image detection/sensing array relative to the imaging lens; and by dynamic focus control. Each of these different methods has been described in detail above.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B the image formation and detection module 3" are fixedly mounted on an optical bench or chassis assembly 8 so as to prevent any relative motion between (i) the image forming optics (e.g. camera lens) within the image formation and detection module 3" and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) employed in the PLIIM-based system which might be caused by vibration or temperature changes. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3", as well as be easy to manufacture, service and repair. Also, this PLIIM-based system employs the general "planar laser illumination" and "FBAFOD" principles described above.

<u>First Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 3B1</u>

The first illustrative embodiment of the PLIIM-Based system of Fig. 3A, indicated by reference numeral 50A, is shown in Fig. 3B1. As illustrated therein, the field of view of the image formation and detection module 3" and the first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations.

The PLIIM-based system 50A illustrated in Fig. 3B1 is shown in greater detail in Fig. 3B2. As shown therein, the linear image formation and detection module 3" is shown comprising an imaging subsystem 3B", and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B". The imaging subsystem 3B" has a variable focal length imaging lens, a variable focal distance and a variable field of view. As shown, each planar laser illumination array 6A, 6B comprises a plurality of planar laser

illumination modules (PLIMs) 11A through 11F, closely arranged relative to each other, in a rectilinear fashion. As taught hereinabove, the relative spacing of each PLIM 11 in the illustrative embodiment is such that the spatial intensity distribution of the individual planar laser beams superimpose and additively provide a composite planar case illumination beam having substantially uniform composite spatial intensity distribution for the entire planar laser illumination array 6A and 6B.

As shown in Fig. 3C1, the PLIIM-based system 50A of Fig. 3B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3"; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3C2 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM-based system of Fig. 3B1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C1 in response to a first set of control signals generated by the camera

control computer 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C1 in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B2 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E2 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

A first preferred implementation of the image formation and detection (IFD) subsystem of Fig. 3C2 is shown in Fig. 3D1. As shown in Fig. 3D1, IFD subsystem 3" comprises: an optical bench 3D having a pair of rails, along which mounted optical elements are translated; a linear CCD-type image detection array 3A (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) fixedly mounted to one end of the optical bench; a system of stationary lenses 3A1 fixedly mounted before the CCD-type linear image detection array 3A; a first system of movable lenses 3B1 slidably mounted to the rails of the optical bench 3D by a set of ball bearings, and designed for stepped movement relative to the stationary lens subsystem 3A1 with translator 3C1 in automatic response to a first set of control signals 3E1 generated by the camera control computer 22; and a second system of movable lenses 3B2 slidably mounted to the rails of the optical bench by way of a second set of ball bearings, and designed for stepped movements relative to the first system of movable lenses 3B with translator 3C2 in automatic response to a second set of control signals 3D2 generated by the camera control computer 22. As shown in Fig. 3D, a large stepper wheel 42 driven by a zoom stepper motor 43 engages a portion of the zoom lens system 3B1 to move the same along the optical axis of the stationary lens system 3A1 in response to control signals 3C1 generated from the camera control computer 22. Similarly, a small stepper wheel 44 driven by a focus stepper motor 45 engages a portion of the focus lens system 3B2 to move the same along the optical axis of the stationary lens system 3A1 in response to control signals 3E2 generated from the camera control computer 22.

A second preferred implementation of the IFD subsystem of Fig. 3C2 is shown in Figs. 3D2 and 3D3. As shown in Figs. 3D2 and 3D3, IFD subsystem 3" comprises: an optical bench (i.e. camera body) 400 having a pair of side rails 401A and 401B, along which mounted optical elements are translated; a linear CCD-type image detection array 3A (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) rigidly mounted to a heat sinking structure 1100 and the rigidly

connected camera body 400, using the image sensor chip mounting arrangement illustrated in Figs. 3D4 through 3D7, and described in detail hereinbelow; a system of stationary lenses 3A1 fixedly mounted before the CCD-type linear image detection array 3A; a first movable (zoom) lens system 402 including a first electrical rotary motor 403 mounted to the camera body 400, an arm structure 404 mounted to the shaft of the motor 403, a first lens mounting fixture 405 (supporting a zoom lens group) 406 slidably mounted to camera body on first rail structure 401A, and a first linkage member 407 pivotally connected to a first slidable lens mount 408 and the free end of the first arm structure 404 so that as the first motor shaft rotates, the first slidable lens mount 405 moves along the optical axis of the imaging optics supported within the camera body; a second movable (focus) lens system 410 including a second electrical rotary motor 411 mounted to the camera body 400, a second arm structure 412 mounted to the shaft of the second motor 411, a second lens mounting fixture 413 (supporting a focal lens group 414) slidably mounted to the camera body on a second rail structure 401B, and a second linkage member 415 pivotally connected to a second slidable lens mount 416 and the free end of the second arm structure 412 so that as the second motor shaft rotates, the second slidable lens mount 413 moves along the optical axis of the imaging optics supported within the camera body. Notably, the first system of movable lenses 406 are designed to undergo relative small stepped movement relative to the stationary lens subsystem 3A1 in automatic response to a first set of control signals 3E1 generated by the camera control computer 22 and transmitted to the first electrical motor 403. The second system of movable lenses 414 are designed to undergo relatively larger stepped movements relative to the first system of movable lenses 406 in automatic response to a second set of control signals 3D2 generated by the camera control computer 22 and transmitted to the second electrical motor 411.

<u>Method Of And Apparatus For Mounting A Linear Image Sensor Chip Within A PLIIM-Based System To Prevent Misalignment Between The Field Of View (FOV) Of Said Linear Image Sensor Chip And The Planar Laser Illumination Beam (PLIB) Used Therewith, In Response To Thermal Expansion or Cycling Within Said PLIIM-Based System</u>

When using a planar laser illumination beam (PLIB) to illuminate the narrow field of view (FOV) of a linear image detection array, even the smallest of misalignment errors between the FOV and the PLIB can cause severe errors in performance within the PLIIM-based system. Notably, as the working/object distance of the PLIIM-based system is made longer, the sensitivity of the system to such FOV/PLIB misalignment errors markedly increases. One of the major causes of such FOV/PLIB misalignment errors is thermal cycling within the PLIIM-based system. As materials used within the PLIIM-based system expand and contract in response to increases and decreases in ambient temperature, the physical structures which serve

to maintain alignment between the FOV and PLIB move in relation to each other. If the movement between such structures becomes significant, then the PLIB may not illuminate the narrow field of view (FOV) of the linear image detection array, causing dark levels to be produced in the images captured by the system without planar laser illumination. In order to mitigate such misalignment problems, the camera subsystem (i.e. IFD module) of the present invention is provided with a novel linear image sensor chip mounting arrangement which helps maintain precise alignment between the FOV of the linear image sensor chip and the PLIB used to illuminate the same. Details regarding this mounting arrangement will be described below with reference to Figs. 3D4 through 3D7.

As shown in Fig. 3D3, the camera subsystem further comprises: heat sinking structure 1100 to which the linear image sensor chip 3A and camera body 400 are rigidly mounted; a camera PC electronics board 1101 for supporting a socket 1108 into which the linear image sensor chip 3A is connected, and providing all of the necessary functions required to operate the linear CCD image sensor chip 3A, and capture high-resolution linear digital images therefrom for buffering, storage and processing.

As best illustrated in Fig. 3D4, the package of the image sensor chip 3A is rigidly mounted and thermally coupled to the back plate 1102 of the heat sinking structure 1100 by a releasable image sensor chip fixture subassembly 1103 which is integrated with the heat sinking structure 1100. The primary function of this image sensor chip fixture subassembly 1103 is to prevent relative movement between the image sensor chip 3A and the heat sinking structure 1100 and camera body 400 during thermal cycling within the PLIIM-based system. At the same time, the image sensor chip fixture subassembly 1103 enables the electrical connector pins 1104 of the image sensor chip to pass freely through four sets of apertures 1105A through 1105D formed through the back plate 1102 of the heat sinking structure, as shown in Fig. 3D5, and establish secure electrical connection with electrical contacts 1107 contained within a matched electrical socket 1108 mounted on the camera PC electronics board 1101, shown in greater detail in Fig. 3D6. As shown in Figs. 3D4 and 3D7, the camera PC electronics board 1101 is mounted to the heat sinking structure 1100 in a manner which permits relative expansion and contraction between the camera PC electronics board 1101 and heat sinking structure 1100 during thermal cycling. Such mounting techniques may include the use of screws or other fastening devices known in the art.

As shown in Fig. 3D5, the releasable image sensor chip fixture subassembly 1103 comprises a number of subcomponents integrated on the heat sinking structure 1100, namely: a set of chip fixture plates 1109, mounted at about 45 degrees with respect to the back plate 1102 of the heat sinking structure, adapted to clamp one side edge of the package of the linear image sensor chip 3A as it is pushed down into chip mounting slot 1110 (provided by clearing away a

rectangular volume of space otherwise occupied by heat exchanging fins 1111 protruding from the back plate 1102), and permit the electrical connector pins 1104 extending from the image sensor chip 3A to pass freely through apertures 1105A through 1105D formed through the back plate 1102; and a set of spring-biased chip clamping pins 1112A and 1112B, mounted opposite the chip fixture plates 1109A and 1109B, for releasably clamping the opposite side of the package of the linear image sensor chip 3A when it is pushed down into place within the chip mounting slot 1110, and securely and rigidly fixing the package of the linear image sensor chip 3A (and thus image detection elements therewithin) relative to the heat sinking structure 1100 and thus the camera body 400 and all of the optical lens components supported therewithin.

As shown in Fig. 3D7, when the linear image sensor chip 3A is mounted within its chip mounting slot 1110, in accordance with the principles of the present invention, the electrical connector pins 1104 of the image sensor chip are freely passed through the four sets of apertures 1105A through 1105D formed in the back plate of the heat sinking structure, while the image sensor chip package 3A is rigidly fixed to the camera system body, via its heat sinking structure. When so mounted, the image sensor chip 3A is not permitted to undergo any significant relative movement with respect to the heat sinking structure and camera body 400 during thermal cycling. However, the camera PC electronics board 1101 may move relative to the heat sinking structure and camera body 400, in response to thermal expansion and contraction during cycling. The result is that the image sensor chip mounting technique of the present invention prevents any misalignment between the field of view (FOV) of the image sensor chip and the PLIA produced by the PLIA within the camera subsystem, thereby improving the performance of the PLIIM-based system during planar laser illumination and imaging operations.

Method of Adjusting the Focal Characteristics of the Planar Laser Illumination Beams (PLIBs) Generated by Planar Laser Illumination Arrays (PLIAs) Used in Conjunction with Image Formation And Detection (IFD) Modules Employing Variable Focal Length (Zoom) Imaging Lenses

Unlike the fixed focal length imaging lens case, there occurs a significant a $1/r^2$ drop-off in laser return light intensity at the image detection array when using a zoom (variable focal length) imaging lens in the PLIIM-based system hereof. In PLIIM-based system employing an imaging subsystem having a variable focal length imaging lens, the area of the imaging subsystem's field of view (FOV) remains constant as the working distance increases. Such variable focal length control is used to ensure that each image formed and detected by the image formation and detection (IFD) module 3" has the same number of "dots per inch" (DPI) resolution, regardless of the distance of the target object from the IFD module 3". However,

since module's field of view does not increase in size with the object distance, equation (8) must be rewritten as the equation (10) set forth below

$$E_{ccd}^{zoom} = \frac{E_0 f^2 s^2}{8d^2 F^2 r^2} \qquad (10)$$

where s^2 is the area of the field of view and d^2 is the area of a pixel on the image detecting array. This expression is a strong function of the object distance, and demonstrates $1/r^2$ drop off of the return light. If a zoom lens is to be used, then it is desirable to have a greater power density at the farthest object distance than at the nearest, to compensate for this loss. Again, focusing the beam at the farthest object distance is the technique that will produce this result.

Therefore, in summary, where a variable focal length (i.e. zoom) imaging subsystem is employed in the PLIIM-based system, the planar laser beam focusing technique of the present invention described above helps compensate for (i) decreases in the power density of the incident illumination beam due to the fact that the width of the planar laser illumination beam increases for increasing distances away from the imaging subsystem, and (ii) any $1/r^2$ type losses that would typically occur when using the planar laser planar illumination beam of the present invention.

<u>Second Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 3A</u>

The second illustrative embodiment of the PLIIM-based system of Fig. 3A, indicated by reference numeral 50B, is shown in Fig. 3E1 as comprising: an image formation and detection module 3" having an imaging subsystem 3B with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3"; and a pair of planar laser illumination arrays 6A and 6B arranged in relation to the image formation and detection module 3" such that the field of view thereof folded by the field of view folding mirror 9 is oriented in a direction that is coplanar with the composite plane of laser illumination 12

produced by the planar illumination arrays, during object illumination and image detection operations, without using any laser beam folding mirrors.

As shown in Fig. 3E2, the PLIIM-based system of Fig. 3E1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3A; a field of view folding mirror 9' for folding the field of view of the image formation and detection module 3"; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3E3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM-based system of Fig. 3E1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B" comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3B2. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C2 in response to a first set of control signals 3E2 generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth

along the optical axis with translator 3C2 in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module 3" with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Detailed Description Of An Exemplary Realization Of The PLIIM-Based System Shown In Fig. 3E1 through 3E3

Referring now to Figs. 3E4 through 3E8, an exemplary realization of the PLIIM-based system, indicated by reference numeral 50B, shown in Figs. 3E1 through 3E3 will now be described in detail below.

As shown in Figs. 3E41 and 3E5, an exemplary realization of the PLIIM-based system 50B shown in Figs. 3E1-3E3 is indicated by reference numeral 25' contained within a compact housing 2 having height, length and width dimensions of about 4.5″, 21.7″ and 19.7″, respectively, to enable easy mounting above a conveyor belt structure or the like. As shown in Fig. 3E4, 3E5 and 3E6, the PLIIM-based system comprises a linear image formation and detection module 3", a pair of planar laser illumination arrays 6A, and 6B, and a field of view (FOV) folding structure (e.g. mirror, refractive element, or diffractive element) 9. The function of the FOV folding mirror 9 is to fold the field of view (FOV) 10 of the image formation and detection module 3' in an imaging direction that is coplanar with the plane of laser illumination beams (PLIBs) 7A and 7B produced by the planar illumination arrays 6A and 6B. As shown, these components are fixedly mounted to an optical bench 8 supported within the compact housing 2 so that these optical components are forced to oscillate together. The linear CCD imaging array 3A can be realized using a variety of commercially available high-speed line-scan camera systems such as, for example, the Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com. Notably, image frame grabber 19, image data buffer (e.g. VRAM) 20, image processing computer 21, and camera control computer 22 are realized on one or more printed circuit (PC) boards contained within a camera and system electronic module 27 also mounted on the optical bench, or elsewhere in the system housing 2.

As shown in Fig. 3E6, a stationary cylindrical lens array 299 is mounted in front of each PLIA (6A, 6B) adjacent the illumination window formed within the optics bench 8 of the PLIIM-

based system 25'. The function performed by cylindrical lens array 299 is to optically combine the individual PLIB components produced from the PLIMs constituting the PLIA, and project the combined PLIB components onto points along the surface of the object being illuminated. By virtue of this inventive feature, each point on the object surface being imaged will be illuminated by different sources of laser illumination located at different points in space (i.e. spatially coherent-reduced laser illumination), thereby reducing the RMS power of speckle-pattern noise observable at the linear image detection array of the PLIIM-based system.

While this system design requires additional optical surfaces (i.e. planar laser beam folding mirrors) which complicates laser-beam/FOV alignment, and attenuates slightly the intensity of collected laser return light, this system design will be beneficial when the FOV of the imaging subsystem cannot have a large apex angle, as defined as the angular aperture of the imaging lens (in the zoom lens assembly), due to the fact that the IFD module 3" must be mounted on the optical bench in a backed-off manner to the conveyor belt (or maximum object distance plane), and a longer focal length lens (or zoom lens with a range of longer focal lengths) is chosen.

One notable advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to be installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3" can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to be practiced in a relatively easy manner.

As shown in Fig. 3E4, the compact housing 2 has a relatively long light transmission window 28 of elongated dimensions for the projecting the FOV 10 of the image formation and detection module 3" through the housing towards a predefined region of space outside thereof, within which objects can be illuminated and imaged by the system components on the optical bench. Also, the compact housing 2 has a pair of relatively short light transmission apertures 30A and 30B, closely disposed on opposite ends of light transmission window 28, with minimal spacing therebetween, as shown in Fig. 3E4. Such spacing is to ensure that the FOV emerging from the housing 2 can spatially overlap in a coplanar manner with the substantially planar laser illumination beams projected through transmission windows 29A and 29B, as close to transmission window 28 as desired by the system designer, as shown in Figs. 3E6 and 3E7. Notably, in some applications, it is desired for such coplanar overlap between the FOV and planar laser illumination beams to occur very close to the light transmission windows 28, 29A

and 29B (i.e. at short optical throw distances), but in other applications, for such coplanar overlap to occur at large optical throw distances.

In either event, each planar laser illumination array 6A and 6B is optically isolated from the FOV of the image formation and detection module 3" to increase the signal-to-noise ratio (SNR) of the system. In the preferred embodiment, such optical isolation is achieved by providing a set of opaque wall structures 30A, 30B about each planar laser illumination array, extending from the optical bench 8 to its light transmission window 29A or 29B, respectively. Such optical isolation structures prevent the image formation and detection module 3" from detecting any laser light transmitted directly from the planar laser illumination arrays 6A and 6B within the interior of the housing. Instead, the image formation and detection module 3" can only receive planar laser illumination that has been reflected off an illuminated object, and focused through the imaging subsystem 3B" of the IFD module 3".

Notably, the linear image formation and detection module of the PLIIM-based system of Fig. 3E4 has an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance, and a variable field of view. In Fig. 3E8, the spatial limits for the FOV of the image formation and detection module are shown for two different scanning conditions, namely: when imaging the tallest package moving on a conveyor belt structure; and when imaging objects having height values close to the surface of the conveyor belt structure. In a PLIIM system having a variable focal length imaging lens and a variable focusing mechanism, the PLIIM system would be capable of imaging at either of the two conditions indicated above.

In order that PLLIM-based subsystem 25′ can be readily interfaced to and an integrated (e.g. embedded) within various types of computer-based systems, as shown in Figs. 9 through 34C, subsystem 25′ also comprises an I/0 subsystem 500 operably connected to camera control computer 22 and image processing computer 21, and a network controller 501 for enabling high-speed data communication with others computers in a local or wide area network using packet-based networking protocols (e.g. Ethernet, AppleTalk, etc.) well known in the art.

<u>Third Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 3A</u>

The third illustrative embodiment of the PLIIM-based system of Fig. 3A, indicated by reference numeral 50C, is shown in Fig. 3F1 as comprising: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-

D line images formed thereon by the imaging subsystem 3B"; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams (PLIBs) 7A and 7B, respectively; and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the FOV of the image formation and detection module 3" during object illumination and imaging operations.

One notable disadvantage of this system architecture is that it requires additional optical surfaces (i.e. the planar laser beam folding mirrors) which reduce outgoing laser light and therefore the return laser light slightly. Also this system design requires a more complicated beam/FOV adjustment scheme than the direct-viewing design shown in Fig. 3B1. Thus, this system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. Notably, in this system embodiment, the PLIMs are mounted on the optical bench as far back as possible from the beam folding mirrors 37A and 37B, and cylindrical lenses 16 with larger radiuses will be employed in the design of each PLIM 11A through 11P.

As shown in Fig. 3F2, the PLIIM-based system of Fig. 3F1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3A; a pair of planar laser illumination beam folding mirrors 37A and 37B, for folding the planar laser illumination beams 7A and 7B in the imaging direction; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3F3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM-based system of Fig. 3F1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A' mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench 3D in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth in response to a first set of control signals generated by the camera control computer, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Fourth Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 3A

The fourth illustrative embodiment of the PLIIM-based system of Fig. 3A, indicated by reference numeral 50D, is shown in Fig. 3G1 as comprising: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a FOV folding mirror 9 for folding the FOV of the imaging subsystem in the direction of imaging; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A, 7B; and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the

planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the FOV of the image formation and detection module during object illumination and image detection operations.

As shown in Fig. 3G2, the PLIIM-based system of Fig. 3G1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; linear-type image formation and detection module 3"; a FOV folding mirror 9 for folding the FOV of the imaging subsystem in the direction of imaging; a pair of planar laser illumination beam folding mirrors 37A and 37B, for folding the planar laser illumination beams 7A and 7B in the imaging direction; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer 20; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3G3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM-based system of Fig. 3G1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C2 in response to a first set of control signals 3E2 generated by the camera

control computer 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3C1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

<u>Applications For The Fifth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention, and the Illustrative Embodiments Thereof</u>

As the PLIIM-based systems shown in Figs. 3A through 3G3 employ an IFD module having a linear image detecting array and an imaging subsystem having variable focal length (zoom) and variable focus (i.e. focal distance) control mechanisms, such PLIIM-based systems are good candidates for use in the conveyor top scanner application shown in Fig. 3H, as variations in target object distance can be up to a meter or more (from the imaging subsystem) and the imaging subsystem provided therein can easily accommodate such object distance parameter variations during object illumination and imaging operations. Also, by adding dynamic focusing functionality to the imaging subsystem of any of the embodiments shown in Figs. 3A through 3F3, the resulting PLIIM-based system will become appropriate for the conveyor side scanning application also shown in Fig. 3G, where the demands on the depth of field and variable focus or dynamic focus requirements are greater compared to a conveyor top scanner application.

<u>Sixth Generalized Embodiment Of The Planar Laser Illumination And Electronic Imaging (PLIIM-Based) System Of The Present Invention</u>

The sixth generalized embodiment of the PLIIM-based system of Fig. 3A, indicated by reference numeral 50', is illustrated in Figs. 3J1 and 3J2. As shown in Fig. 3J1, the PLIIM-based system 50' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3"; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3". During system operation, laser illumination arrays 6A and 6B each produce a composite laser illumination beam 12 which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the

image formation and detection module 3", so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 2-D scanning region.

As shown in Figs. 3J2 and 3J3, the PLIIM-based system of Fig. 3J1 50' comprises: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a field of view folding and sweeping mirror 9' for folding and sweeping the field of view of the image formation and detection module 3"; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam folding and sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 3J3, each planar laser illumination module 11A through 11F is driven by a VLD driver circuit 18 under the camera control computer 22 in a manner well known in the art. Notably, laser illumination beam folding/sweeping mirror 37A' and 37B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 39A, 39B, and 38, respectively, operated under the control of the camera control computer 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which are synchronously controlled to enable the planar laser illumination beams and FOV to move together during illumination and detection operations within the PLIIM system.

Fig. 3J4 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM-based system of Fig. 3J1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical

bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B" comprises: a first group of focal lens elements 3B" mounted stationary relative to the image detecting array 3A1 a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth in response to a first set of control signals generated by the camera control computer, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C2 in response to a first set of control signals 3E1 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3", the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3" and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM-based system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B, beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3" and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

Applications For The Sixth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention

As the PLIIM-based systems shown in Figs. 3J1 through 3J4 employ (i) an IFD module having a linear image detecting array and an imaging subsystem having variable focal length (zoom) and variable focal distance control mechanisms, and also (ii) a mechanism for automatically sweeping both the planar (2-D) FOV and planar laser illumination beam through a 3-D scanning field in a raster-like pattern while maintaining the inventive principle of "laser-beam/FOV coplanarity" herein disclosed, such PLIIM systems are good candidates for use in a hand-held scanner application, shown in Fig. 3J5, and the hands-free presentation scanner application illustrated in Fig. 3J6. As such, these embodiments of the present invention are ideally suited for use in hand-supportable and presentation-type hold-under bar code symbol reading applications shown in Figs. 3J5 and 3J6, respectively, in which raster--like ("up and down") scanning patterns can be used for reading 1-D as well as 2-D bar code symbologies such as the PDF 147 symbology. In general, the PLIIM-based system of this generalized embodiment may have any of the housing form factors disclosed and described in Applicant's copending US Application No. 09/204,176 filed December 3, 1998, U.S. Application No. 09/452,976 filed December 2, 1999, and WIPO Publication No. WO 00/33239 published June 8, 2000 incorporated herein by reference. The beam sweeping technology disclosed in copending Application No. 08/931,691 filed September 16, 1997, incorporated herein by reference, can be used to uniformly sweep both the planar laser illumination beam and linear FOV in a coplanar manner during illumination and imaging operations.

Seventh Generalized Embodiment Of The PLIIM-Based System Of The Present Invention

The seventh generalized embodiment of the PLIIM-based system of the present invention, indicated by reference numeral 60, is illustrated in Fig. 4A. As shown therein, the PLIIM-based system 60 comprises: a housing 2 of compact construction; an area (i.e. 2-D) type image formation and detection (IFD) module 55 including a 2-D electronic image detection array 55A, and an area (2-D) imaging subsystem (LIS) 55B having a fixed focal length, a fixed focal distance, and a fixed field of view (FOV), for forming a 2-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55, for producing

first and second planes of laser beam illumination 7A and 7B that are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of image formation and detection module 55 during object illumination and image detection operations carried out by the PLIIM system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55, and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55 and any stationary FOV folding mirror employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each planar laser illumination beam folding/sweeping mirror employed in the PLIIM-based system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55, as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

<u>First Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 4A</u>

The first illustrative embodiment of the PLIIM-Based system of Fig. 4A, indicated by reference numeral 60A, is shown in Fig. 4B1 as comprising: an image formation and detection module (i.e. camera) 55 having an imaging subsystem 55B with a fixed focal length imaging lens, a fixed focal distance and a fixed field of view (FOV) of three-dimensional extent, and an area (2-D) array of photo-electronic detectors 55A realized using high-speed CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D arean images formed thereon by the imaging subsystem 55B; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams 7A, 7B are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the 3-D FOV 40' of

image formation and detection module during object illumination and image detection operations carried out by the PLIIM-based system.

As shown in Fig. 4B3, the PLIIM-based system 60A of Fig. 4B1 comprises: planar laser illumination arrays (PLIAs) 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; area-type image formation and detection module 55; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

<u>Second Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 4A</u>

The second illustrative embodiment of the PLIIM-based system of Fig. 4A, indicated by reference numeral 601, is shown in Fig. 4C1 as comprising: an image formation and detection module 55 having an imaging subsystem 55B with a fixed focal length imaging lens, a fixed focal distance and a fixed field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of PLIB folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively,

such that the planar laser illumination beams (PLIBs) 7A, 7B are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM-based system.

In general, the arean image detection array 55B employed in the PLIIM systems shown in Figs. 4A through 6F4 has multiple rows and columns of pixels arranged in a rectangular array. Therefore, arean image detection array is capable of sensing/detecting a complete 2-D image of a target object in a single exposure, and the target object may be stationary with respect to the PLIIM-based system. Thus, the image detection array 55D is ideally suited for use in hold-under type scanning systems However, the fact that the entire image is captured in a single exposure implies that the technique of dynamic focus cannot be used with an arean image detector.

As shown in Fig. 4C2, the PLIIM-based system of Fig. 4C1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11B, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; area-type image formation and detection module 55B; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof, including synchronous driving motors 58A and 68B, in an orchestrated manner.

Applications For The Seventh Generalized Embodiment Of The PLIIM-Based System Of The Present Invention, and the Illustrative Embodiments Thereof

The fixed focal distance area-type PLIIM-based systems shown in Figs. 4A through 4C2 are ideal for applications in which there is little variation in the object distance, such as in a 2-D hold-under scanner application as shown in Fig. 4D. A fixed focal distance PLIIM-based system generally takes up less space than a variable or dynamic focus model because more advanced focusing methods require more complicated optics and electronics, and additional components such as motors. For this reason, fixed focus PLIIM systems are good choices for the hands-free presentation and hand-held scanners applications illustrated in Figs. 4D and 4E, respectively, wherein space and weight are always critical characteristics. In these applications, however, the object distance can vary over a range from several to twelve or more inches, and so the designer must exercise care to ensure that the scanner's depth of field (DOF) alone will be sufficient to accommodate all possible variations in target object distance and orientation. Also, because a fixed focus imaging subsystem implies a fixed focal length imaging lens, the variation in object distance implies that the dpi resolution of acquired images will vary as well, and therefore image-based bar code symbol decode-processing techniques must address such variations in image resolution. The focal length of the imaging lens must be chosen so that the angular width of the field of view (FOV) is narrow enough that the dpi image resolution will not fall below the minimum acceptable value anywhere within the range of object distances supported by the PLIIM system.

Eighth Generalized Embodiment Of The PLIIM System Of The Present Invention

The eighth generalized embodiment of the PLIIM system of the present invention 70 is illustrated in Fig. 5A. As shown therein, the PLIIM system 70 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55' including a 2-D electronic image detection array 55A, an area (2-D) imaging subsystem (LIS) 55B' having a fixed focal length, a variable focal distance, and a fixed field of view (FOV), for forming a 2-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55', for producing first and second planes of laser beam illumination 7A and 7B such that the 3-D field of view 10' of the image formation and detection

module 55' is disposed substantially coplanar with the planes of the first and second PLIBs 7A, 7B during object illumination and image detection operations carried out by the PLIIM system. While possible, this system configuration would be difficult to use when packages are moving by on a high-speed conveyor belt, as the planar laser illumination beams would have to sweep across the package very quickly to avoid blurring of the acquired images due to the motion of the package while the image is being acquired. Thus, this system configuration might be better suited for a hold-under scanning application, as illustrated in Fig. 5D, wherein a person picks up a package, holds it under the scanning system to allow the bar code to be automatically read, and then manually routes the package to its intended destination based on the result of the scan.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55', and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55' and any stationary FOV folding mirror employed therewith, and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) 55' and each PLIB folding/sweeping mirror employed in the PLIIM-based system configuration. Preferably, the chassis assembly 8 should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays (PLIAs) 6A and 6B as well as the image formation and detection module 55', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM-based system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

<u>First Illustrative Embodiment Of The PLIIM-Based System Shown In Fig. 5A</u>

The first illustrative embodiment of the PLIIM-based system of Fig. 5A, indicated by reference numeral, indicated by reference numeral 70A, is shown in Figs. 5B1 and 5B2 as comprising: an image formation and detection module 55' having an imaging subsystem 55B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view (of 3-D spatial extent), and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D images formed thereon by the imaging subsystem 55B'; a pair of planar laser

illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams 7A, 7B are disposed substantially coplanar with a section of the 3-D FOV (10') of the image formation and detection module 55' during object illumination and imaging operations carried out by the PLIIM-based system.

As shown in Fig. 5B3, PLIIM-based system 70A comprises: planar laser illumination arrays 6A and 6B each having a plurality of planar laser illumination modules (PLIMs) 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; area-type image formation and detection module 55'; PLIB folding/sweeping mirrors 57A and 57B, driven by motors 58A and 58B, respectively; a high-resolution image frame grabber 19 operably connected to area-type image formation and detection module 55A, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays (PLIAs) 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. The operation of this system configuration is as follows. Images detected by the low-resolution area camera 61 are grabbed by the image frame grabber 62 and provided to the image processing computer 21 by the camera control computer 22. The image processing computer 21 automatically identifies and detects when a label containing a bar code symbol structure has moved into the 3-D scanning field, whereupon the high-resolution CCD detection array camera 55A is automatically triggered by the camera control computer 22. At this point, as the planar laser illumination beams 12' begin to sweep the 3-D scanning region, images are captured by the high-resolution array 55A and the image processing computer 21 decodes the detected bar code by a more robust bar code symbol decode software program.

Fig. 5B4 illustrates in greater detail the structure of the IFD module 55' used in the PLIIM-base system of Fig. 5B3. As shown, the IFD module 55' comprises a variable focus fixed focal length imaging subsystem 55B' and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). The imaging subsystem 55B' comprises a group of stationary lens elements 55B1' mounted along the optical bench before the image detecting array 55A, and a group of focusing lens elements 55B2' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 55B1'. In a non-customized application, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C in response to a first set of control signals 55E generated by the camera control computer 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 55B2' back and forth with translator 55C in response to a first set of control signals 55E generated by the camera control computer, while the 2-D image detecting array 55A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 55B2' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 55' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 5A

The second illustrative embodiment of the PLIIM-based system of Fig. 5A is shown in Figs. 5C1, 5C2 comprising: an image formation and detection module 55' having an imaging subsystem 55B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B, wherein each VLD 11 is driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 bring provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally

integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module 55' during object illumination and image detection operations carried out by the PLIIM-based system.

As shown in Fig. 5C3, the PLIIM-based system 70A of Fig. 5C1 is shown in slightly greater detail comprising: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 3- frames/second or so); planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55'; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B, driven by motors 58A and 58B, respectively; an image frame grabber 19 operably connected to area-type image formation and detection module 55', for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 5C4 illustrates in greater detail the structure of the IFD module 55' used in the PLIIM-based system of Fig. 5C1. As shown, the IFD module 55' comprises a variable focus fixed focal length imaging subsystem 55B' and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). The imaging subsystem 55B' comprises a group of stationary lens elements 55B1 mounted along the optical bench before the image detecting array 55A, and a group of focusing lens elements 55B2 (having

a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 55B1. In a non-customized application, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C in response to a first set of control signals 55E generated by the camera control computer 22, while the entire group of focal lens elements 55B1 remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 55B2 back and forth with the translator 55C in response to a first set of control signals 55E generated by the camera control computer, while the 2-D image detecting array 55A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 55B2 to be moved in response to control signals generated by the camera control computer. Regardless of the approach taken, the IFD module 55B' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Eighth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention, and the Illustrative Embodiments Thereof

As the PLIIM-based systems shown in Figs. 5A through 5C4 employ an IFD module having an arean image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, such PLIIM-based systems are good candidates for use in a presentation scanner application, as shown in Fig. 5D, as the variation in target object distance will typically be less than 15 or so inches from the imaging subsystem. In presentation scanner applications, the variable focus (or dynamic focus) control characteristics of such PLIIM-based system will be sufficient to accommodate for expected target object distance variations.

Ninth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention

The ninth generalized embodiment of the PLIIM-based system of the present invention, indicated by reference numeral 80, is illustrated in Fig. 6A. As shown therein, the PLIIM-based system 80 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55' including a 2-D electronic image detection array 55A, an area (2-D) imaging subsystem (LIS) 55B" having a variable focal length, a variable focal distance, and a variable field of view (FOV) of 3-D spatial extent, for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data

set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55", for producing first and second planes of laser beam illumination 7A and 7B such that the field of view of the image formation and detection module 55" is disposed substantially coplanar with the planes of the first and second planar laser illumination beams during object illumination and image detection operations carried out by the PLIIM system. While possible, this system configuration would be difficult to use when packages are moving by on a high-speed conveyor belt, as the planar laser illumination beams would have to sweep across the package very quickly to avoid blurring of the acquired images due to the motion of the package while the image is being acquired. Thus, this system configuration might be better suited for a hold-under scanning application, as illustrated in Fig. 5D, wherein a person picks up a package, holds it under the scanning system to allow the bar code to be automatically read, and then manually routes the package to its intended destination based on the result of the scan.

In accordance with the present invention, the planar laser illumination arrays (PLIAs) 6A and 6B, the linear image formation and detection module 55", and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55" and any stationary FOV folding mirror employed therewith, and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each PLIB folding/sweeping mirror employed in the PLIIM-based system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55", as well as be easy to manufacture, service and repair. Also, this generalized PLIIM-based system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

<u>First Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 6A</u>

The first illustrative embodiment of the PLIIM-based system of Fig. 6A, indicated by reference numeral 80A, is shown in Figs. 6B1 and 6B2 as comprising: an area-type image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and an area (2-D)

array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55A; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of PLIB folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of image formation and detection module during object illumination and image detection operations carried out by the PLIIM-based system.

As shown in Fig. 6B3, the PLIIM-based system of Fig. 6B1 comprises: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 3- frames/second or so); planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; area-type image formation and detection module 55B; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55", for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 6B4 illustrates in greater detail the structure of the IFD module 55" used in the PLIIM-based system of Fig. 6B31. As shown, the IFD module 55" comprises a variable focus variable focal length imaging subsystem 55B" and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). In general, the imaging subsystem 55B" comprises: a first group of focal lens elements 55B1 mounted stationary relative to the image detecting array 55A; a second group of lens elements 55B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 55B1; and a third group of lens elements 55B3, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements 55B2 and the first group of stationary focal lens elements 55B1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 55B2 back and forth with translator 55C1 in response to a first set of control signals generated by the camera control computer, while the 2-D image detecting array 55A remains stationary. Alternatively, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis in response to a first set of control signals 55E2 generated by the camera control computer 22, while the second group of focal lens elements 55B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 55B3 are typically moved relative to each other with translator 55C2 in response to a second set of control signals 55E2 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

<u>Second Illustrative Embodiment Of The PLIIM-Based System Of The Present Invention Shown In Fig. 6A</u>

The second illustrative embodiment of the PLIIM-based system of Fig. 6A, indicated by reference numeral 80B, is shown in Fig. 6C1 and 6C2 as comprising: an image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55B"; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination

beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays (PLIAs) 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 6C3, the PLIIM-based system of Figs. 6C1 and 6C2 comprises: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 30 frames/second or so); planar laser illumination arrays (PLIAs) 6A and 6B, each having a plurality of planar laser illumination modules (PLIMs) 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; area-type image formation and detection module 55A; FOV folding mirror 9; PLIB folding/sweeping mirrors 57A and 57B; a high-resolution image frame grabber 19 operably connected to area-type image formation and detection module 55" for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays (PLIA) 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabbers 62 and 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 6C4 illustrates in greater detail the structure of the IFD module 55" used in the PLIIM-based system of Fig. 6C1. As shown, the IFD module 55" comprises a variable focus variable focal length imaging subsystem 55B" and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). In general, the

imaging subsystem 55B" comprises: a first group of focal lens elements 55B1 mounted stationary relative to the image detecting array 55A; a second group of lens elements 55B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 55A1; and a third group of lens elements 55B3, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements 55B2 and the first group of stationary focal lens elements 55B1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 55B2 back and forth with translator 55C1 in response to a first set of control signals 55E1 generated by the camera control computer 22, while the 2-D image detecting array 55A remains stationary. Alternatively, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C1 in response to a first set of control signals 55A generated by the camera control computer 22, while the second group of focal lens elements 55B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 55B3 are typically moved relative to each other with translator in response to a second set of control signals 55E2 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD (i.e. camera) module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

<u>Applications For The Ninth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention</u>

As the PLIIM-based systems shown in Figs. 6A through 6C4 employ an IFD module having an area-type image detecting array and an imaging subsystem having variable focal length (zoom) and variable focal distance (focus) control mechanism, such PLIIM-based systems are good candidates for use in presentation scanner applications, as shown in Fig. 6C5, as the variation in target object distance will typically be less than 15 or so inches from the imaging subsystem. In presentation scanner applications, the variable focus (or dynamic focus) control characteristics of such PLIIM system will be sufficient to accommodate for expected target object distance variations. All digital images acquired by this PLIIM-based system will have substantially the same dpi image resolution, regardless of the object's distance during illumination and imaging operations. This feature is useful in 1-D and 2-D bar code symbol reading applications.

Exemplary Realization Of The PLIIM-Based System Of The Present Invention, Wherein A Pair Of Coplanar Laser Illumination Beams Are Controllably Steered About A 3-D Scanning Region

In Figs. 6D1 through 6D5, there is shown an exemplary realization of the PLIIM-based system of Fig. 6A. As shown, PLIIM-based system 25″ comprises: an image formation and detection module 55′; a stationary field of view (FOV) folding mirror 9 for folding and projecting the FOV through a 3-D scanning region; a pair of planar laser illumination arrays (PLIAs) 6A and 6B; and pair of PLIB folding/sweeping mirrors 57A and 57B for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module 55″ as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations. As shown in Fig. 6D3, the FOV of the area-type image formation and detection (IFD) module 55″ is folded by the stationary FOV folding mirror 9 and projected downwardly through a 3-D scanning region. The planar laser illumination beams produced from the planar laser illumination arrays (PLIAs) 6A and 6B are folded and swept by mirror 57A and 57B so that the optical paths of these planar laser illumination beams are oriented in a direction that is coplanar with a section of the FOV of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations. As shown in Fig. 6D5, PLIIM-based system 25″ is capable of auto-zoom and auto-focus operations, and producing images having constant dpi resolution regardless of whether the images are of tall packages moving on a conveyor belt structure or objects having height values close to the surface height of the conveyor belt structure.

As shown in Fig. 6D2, a stationary cylindrical lens array 299 is mounted in front of each PLIA (6A, 6B) provided within the PLIIM-based subsystem 25″. The function performed by cylindrical lens array 299 is to optically combine the individual PLIB components produced from the PLIMs constituting the PLIA, and project the combined PLIB components onto points along the surface of the object being illuminated. By virtue of this inventive feature, each point on the object surface being imaged will be illuminated by different sources of laser illumination located at different points in space (i.e. spatially coherent-reduced laser illumination), thereby reducing the RMS power of speckle-pattern noise observable at the linear image detection array of the PLIIM-based subsystem.

In order that PLLIM-based subsystem 25″ can be readily interfaced to and integrated (e.g. embedded) within various types of computer-based systems, as shown in Figs. 9 through 34C, subsystem 25″ further comprises an I/0 subsystem 500 operably connected to camera control computer 22 and image processing computer 21, and a network controller 501 for

enabling high-speed data communication with other computers in a local or wide area network using packet-based networking protocols (e.g. Ethernet, AppleTalk, etc.) well know in the art.

Tenth Generalized Embodiment Of The PLIIM-Based System Of The Present Invention, Wherein A 3-D Field Of View And A Pair Of Planar Laser Illumination Beams Are Controllably Steered About A 3-D Scanning Region

Referring to Figs. 6E1 through 6E4, the tenth generalized embodiment of the PLIIM-based system of the present invention 90 will now be described, wherein a 3-D field of view 101 and a pair of planar laser illumination beams (PLIBs) are controllably steered about a 3-D scanning region in order to achieve a greater region of scan coverage.

As shown in Fig. 6E2, PLIIM-based system of Fig. 6E1 comprises: an area-type image formation and detection module 55'; a pair of planar laser illumination arrays 6A and 6B; a pair of x and y axis field of view (FOV) sweeping mirrors 91A and 91B, driven by motors 92A and 92B, respectively, and arranged in relation to the image formation and detection module 55"; and a pair of x and y planar laser illumination beam (PLIB) folding and sweeping mirrors 57A and 57B, driven by motors 94A and 94B, respectively, so that the planes of the laser illumination beams 7A, 7B are coplanar with a planar section of the 3-D field of view (101) of the image formation and detection module 55" as the PLIBs and the FOV of the IFD module 55" are synchronously scanned across a 3-D region of space during object illumination and image detection operations.

As shown in Fig. 6E3, the PLIIM-based system of Fig. 6E2 comprises: area-type image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view (FOV) of 3-D spatial extent, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D images formed thereon by the imaging subsystem 55A; planar laser illumination arrays, 6A, 6B, wherein each VLD 11 is driven by a VLD driver circuit 18 embodying a digitally-programmable potentiometer (e.g. 763 as shown in Fig. 1I15D for current control purposes) and a microcontroller 764 being provided for controlling the output optical power thereof; a stationary cylindrical lens array 299 mounted in front of each PLIA (6A, 6B) and ideally integrated therewith, for optically combining the individual PLIB components produced from the PLIMs constituting the PLIA, and projecting the combined PLIB components onto points along the surface of the object being illuminated; x and y axis FOV steering mirrors 91A and 91B; x and y axis PLIB sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55A, for accessing 2-D digital

images of the object being illuminated by the planar laser illumination arrays (PLIAs) 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Area-type image formation and detection module 55" can be realized using a variety of commercially available high-speed area-type CCD camera systems such as, for example, the KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor, from Eastman Kodak Company-Microelectronics Technology Division—Rochester, New York.

Fig. 6E4 illustrates a portion of the PLIIM-based system 90 shown in Fig. 6E1, wherein the 3-D field of view (FOV) of the image formation and detection module 55" is shown steered over the 3-D scanning region of the system using a pair of x and y axis FOV folding mirrors 91A and 91B, which work in cooperation with the x and y axis PLIB folding/steering mirrors 57A and 57B to steer the pair of planar laser illumination beams (PLIBs) 7A and 7B in a coplanar relationship with the 3-D FOV (101), in accordance with the principles of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection (IFD) module 55", FOV folding/sweeping mirrors 91A and 91B, and PLIB folding/sweeping mirrors 57A and 57B employed in this system embodiment, are mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55" and FOV folding/sweeping mirrors 91A, 91B employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each PLIB folding/sweeping mirror 57A and 57B employed in the PLIIM-based system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55", as well as be easy to manufacture, service and repair. Also, this PLIIM-based system embodiment employs the general "planar laser illumination beam" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM-based system will be described below.

First Illustrative Embodiment Of The Hybrid Holographic/CCD PLIIM-Based System Of The Present Invention

In Fig. 7A, a first illustrative embodiment of the hybrid holographic/CCD PLIIM-based system of the present invention 100 is shown, wherein a holographic-based imaging subsystem is used to produce a wide range of discrete field of views (FOVs), over which the system can acquire images of target objects using a linear image detection array having a 2-D field of view (FOV) that is coplanar with a planar laser illumination beam in accordance with the principles of the present invention. In this system configuration, it is understood that the PLIIM-based system will be supported over a conveyor belt structure which transports packages past the PLIIM-based system 100 at a substantially constant velocity so that lines of scan data can be combined together to construct 2-D images upon which decode image processing algorithms can be performed.

As illustrated in Fig. 7A, the hybrid holographic/CCD PLIIM-based system 100 comprises: (i) a pair of planar laser illumination arrays 6A and 6B for generating a pair of planar laser illumination beams 7A and 7B that produce a composite planar laser illumination beam 12 for illuminating a target object residing within a 3-D scanning volume; a holographic-type cylindrical lens 101 is used to collimate the rays of the planar laser illumination beam down onto the conveyor belt surface; and a motor-driven holographic imaging disc 102, supporting a plurality of transmission-type volume holographic optical elements (HOE) 103, as taught in U.S. Patent No. 5,984,185, incorporated herein by reference. Each HOE 103 on the imaging disc 102 has a different focal length, which is disposed before a linear (1-D) CCD image detection array 3A. The holographic imaging disc 102 and image detection array 3A function as a variable-type imaging subsystem that is capable of detecting images of objects over a large range of object distances within the 3-D FOV (10") of the system while the composite planar laser illumination beam 12 illuminates the object.

As illustrated in Fig. 7A, the PLIIM-based system 100 further comprises: an image frame grabber 19 operably connected to linear-type image formation and detection module 3A, for accessing 1-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during object illumination and imaging operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 7B, a coplanar relationship exists between the planar laser illumination beam(s) produced by the planar laser illumination arrays 6A and 6B, and the variable field of view (FOV) 10" produced by the variable holographic-based focal length imaging subsystem described above. An advantage of this hybrid PLIIM-based system design is that it also enables the generation of a 3-D image-based scanning volume having multiple depths of focus by virtue of its holographic-based variable focal length imaging subsystem.

Second Illustrative Embodiment Of The Hybrid Holographic/CCD PLIIM-Based System Of The Present Invention

In Fig. 8A, a second illustrative embodiment of the hybrid holographic/CCD PLIIM-based system of the present invention 100' is shown, wherein a holographic-based imaging subsystem is used to produce a wide range of discrete field of views (FOVs), over which the system can acquire images of target objects using an area-type image detection array having a 3-D field of view (FOV) that is coplanar with a planar laser illumination beam in accordance with the principles of the present invention. In this system configuration, it is understood that the PLIIM system 100' can used in a holder-over type scanning application, hand-held scanner application, or presentation-type scanner.

As illustrated in Fig. 8A, the hybrid holographic/CCD PLIIM-based system 101' comprises: (i) a pair of planar laser illumination arrays 6A and 6B for generating a pair of planar laser illumination beams (PLIBs) 7A and 7B; a pair of PLIB folding/sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams (PLIBs) through the 3-D field of view of the imaging subsystem; a holographic-type cylindrical lens 101 for collimating the rays of the planar laser illumination beam down onto the conveyor belt surface; and a motor-driven holographic imaging disc 102, supporting a plurality of transmission-type volume holographic optical elements (HOE) 103, as the disc is rotated about its rotational axis. Each HOE 103 on the imaging disc has a different focal length, and is disposed before an area (2-D) type CCD image detection array 55A. The holographic imaging disc 102 and image detection array 55A function as a variable-type imaging subsystem that is capable of detecting images of objects over a large range of object (i.e. working) distances within the 3-D FOV (10") of the system while the composite planar laser illumination beam 12 illuminates the object.

As illustrated in Fig. 8A, the PLIIM-based system 101' further comprises: an image frame grabber 19 operably connected to an area-type image formation and detection module 55", for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during object illumination and imaging operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image

processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 8B, a coplanar relationship exists between the planar laser illumination beam(s) produced by the planar laser illumination arrays (PLIAs) 6A and 6B, and the variable field of view (FOV) 10" produced by the variable holographic-based focal length imaging subsystem described above. The advantage of this hybrid system design is that it enables the generation of a 3-D image-based scanning volume having multiple depths of focus by virtue of the holographic-based variable focal length imaging subsystem employed in the PLIIM system.

<u>First Illustrative Embodiment Of The Unitary Package Identification And Dimensioning System Of The Present Invention Embodying A PLIIM-Based Subsystem Of The Present Invention And A LADAR-Based Imaging, Detecting And Dimensioning Subsystem</u>

Referring now to Figs. 9, 10 and 11, a unitary package identification and dimensioning system of the first illustrated embodiment 120 will now be described in detail.

As shown in Fig. 10, the unitary system 120 of the present invention comprises an integration of subsystems, contained within a single housing of compact construction supported above the conveyor belt of a high-speed conveyor subsystem 121, by way of a support frame or like structure. In the illustrative embodiment, the conveyor subsystem 121 has a conveyor belt width of at least 48 inches to support one or more package transport lanes along the conveyor belt. As shown in Fig. 10, the unitary system comprises four primary subsystem components, namely: (1) a LADAR-based package imaging, detecting and dimensioning subsystem 122 capable of collecting range data from objects on the conveyor belt using a pair of multi-wavelength (i.e. containing visible and IR spectral components) laser scanning beams projected at different angular spacings as taught in copending US Application No. 09/327,756 filed June 7, 1999, supra, and International PCT Application No. PCT/US00/15624 filed June 7, 2000, incorporated herein by reference, and now published as WIPO Publication No. WO 00/75856 A1, on December 14, 2000; (2) a PLIIM-based bar code symbol reading subsystem 25', as shown in Figs. 3E4 through 3E8, for producing a scanning volume above the conveyor belt, for scanning bar codes on packages transported therealong; (3) an input/output subsystem 127 for managing the inputs to and outputs from the unitary system, including inputs from subsystem 25'; (4) a data management computer 129 with a graphical user interface (GUI) 130, for realizing a data element queuing, handling and processing subsystem 131, as well as other data and system management functions; and (5) and a network controller 132, operably connected to the

I/O subsystem 127, for connecting the system 120 to the local area network (LAN) associated with the tunnel-based system, as well as other packet-based data communication networks supporting various network protocols (e.g. Ethernet, IP, etc). Also, the network communication controller 132 enables the unitary system to receive data inputs from a number of input devices including, for example: weighing-in-motion subsystem 132, shown in Fig. 10 for weighing packages as they are transported along the conveyor belt; an RF-tag reading subsystem for reading RF tags on packages as they are transported along the conveyor belt; an externally mounted belt tachometer for measuring the instant velocity of the belt and package transported therealong; etc. In addition, an optical filter (FO) network controller 133 may be provided for supporting the Ethernet or other network protocol over a filter optical cable communication medium. The advantage of fiber optical cable is that it can be run thousands of feet within and about an industrial work environment while supporting high information transfer rates (required for image lift and transfer operations) without information loss. This fiber-optic data communication interface enables the tunnel-based system of Fig. 9 to be installed thousands of feet away from a keying station in a package routing hub (i.e. center), where lifted digital images and OCR (or barcode) data are simultaneously displayed on the display of a computer work station. Each bar code and/or OCR image processed by tunnel system 120 is indexed in terms of a probabilistic reliability measure, and if the measure falls below a predetermined threshold, then the lifted image and bar code and/or OCR data are simultaneously displayed for a human "key" operator to verify and correct file data, if necessary.

While a LADAR-based package imaging, detecting and dimensioning subsystem 122 is shown embodied within system 120, it is understood that other types of package imaging, detecting and dimensioning subsystems based on non-LADAR height/range data acquisition techniques (e.g. laser-illumination/CCD-imaging based triangulation techniques) may be used to realize the unitary package identification and dimensioning system of the present invention.

As shown in Fig. 10, the LADAR-based package imaging, detecting and dimensioning subsystem 122 comprises an integration of subsystems, namely: a package velocity measurement subsystem 123, for measuring the velocity of transported packages by analyzing range-based height data maps generated by the different angularly displaced AM laser scanning beams of the subsystem, using the inventive methods disclosed in International PCT Application No. PCT/US00/15624 filed December 7, 2000, supra; a package-in-the-tunnel (PITT) indication (i.e. detection) subsystem 125, for automatically detecting the presence of each package moving through the scanning volume by reflecting a portion of one of the laser scanning beams across the width of the conveyor belt in a retro-reflective manner and then analyzing the return signal using first derivative and thresholding techniques disclosed in International PCT Application No. PCT/US00/15624 filed December 7, 2000; a package (x-y)

height/width/length dimensioning (or profiling) subsystem 124, integrated within subsystem 122, for producing x,y,z profile data sets for detected packages, referenced against one or more coordinate reference systems symbolically embedded within subsystem 122, and/or unitary system 120; and a package-out-of-the-tunnel (POOT) indication (i.e. detection) subsystem 125, integrated within subsystem 122, realized using, for example, predictive techniques based on the output of the PITT indication subsystem 125, for automatically detecting the presence of packages moving out of the scanning volume.

The primary function of LDIP subsystem 122 is to measure dimensional characteristics of packages passing through the scanning volume, and produce package dimension data (i.e. a package data element) for each dimensioned package. The primary function of image-based scanning subsystem 25′ is to read bar code symbols on dimensioned packages and produce package identification data (e.g. package data element) representative of each identified package. The primary function of the I/O subsystem 127 is to transport package dimension data elements and package identification data elements to the data element queuing, handling and processing subsystem 131. The primary function of the data element queuing, handling and processing subsystem 131 is to link each package dimension data element with its corresponding package identification data element, and to transport such data element pairs to an appropriate host system for subsequent use (e.g. package routing subsystems, cost-recovery subsystems, etc.). By embodying subsystem 25′ and LDIP subsystem 122 within a single housing 121, an ultra-compact device is provided that can dimension, identify and track packages moving along the package conveyor without requiring the use of any external peripheral input devices, such as tachometers, light-curtains, etc.

In Fig. 11, the subsystem architecture of unitary PLIIM-based package dimensioning and identification system 140 is schematically illustrated in greater detail. As shown, various information signals (e.g., Velocity(t), Intensity(t), Height(t), Width(t), Length(t)) are automatically generated by LDIP subsystem 122 and provided to the camera control computer 22 embodied within PLIIM-based subsystem 25′. Notably, the Intensity(t) data signal generated from LDIP subsystem 122 represents the magnitude component of the polar-coordinate referenced range-map data stream, and specifies the "surface reflectivity" characteristics of the scanned package. The function of the camera control computer 22 is to generate digital camera control signals which are provided to the IFD subsystem (i.e. " variable zoom/focus camera") 3" so that subsystem 25′ can carry out its diverse functions in an integrated manner, including, but not limited to: (1) automatically capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art

systems; (2) automatically cropping captured digital images so that digital data concerning only "regions of interest" reflecting the spatial boundaries of a package wall surface or a package label are transmitted to the image processing computer 21 for (i) image-based bar code symbol decode-processing, and/or (ii) OCR-based image processing; and (3) automatic digital image-lifting operations for supporting other package management operations carried out by the end-user.

During system operation, the PLIIM-based subsystem 25′ automatically generates and buffers digital images of target objects passing within the field of view (FOV) thereof. These images, image cropping indices, and possibly cropped image components, are then transmitted to image processing computer 21 for decode-processing and generation of package identification data representative of decoded bar code symbols on the scanned packages. Each such package identification data element is then provided to data management computer 129 via I/O subsystem 127 (as shown in Fig. 10) for linking with a corresponding package dimension data element, as described in hereinabove. Optionally, the digital images of packages passing beneath the PLIIM-based subsystem 25′ can be acquired (i.e. lifted) and processed by image processing computer 21 in diverse ways (e.g. using OCR programs) to extract other relevant features of the package (e.g. identity of sender, origination address, identity of recipient, destination address, etc.) which might be useful in package identification, tracking, routing and/or dimensioning operations. Details regarding the cooperation of the LDIP subsystem 122, the camera control computer 22, the IFD Subsystem 3″ and the image processing computer 21 will be described herein after with reference to Figs. 20 through 29.

In Figs. 12A and 12B, the physical construction and packaging of unitary system 120 is shown in greater detail. As shown, PLIIM-based subsystem 25' of Figs. 3E1-3E8 and LDIP subsystem 122 are contained within specially-designed, dual-compartment system housing design 161 shown in Figs. 12A and 12B to be described in detail below.

As shown in Fig. 12A, the PLIIM-based subsystem 25' is mounted within a first optically-isolated compartment 162 formed in system housing 161, whereas the LDIP subsystem 122 and associated beam folding mirror 163 are mounted within a second optically isolated compartment 164 formed therein below the first compartment 162. Both optically isolated compartments are realized using optically-opaque wall structures. As shown in Fig. 12A, a first set of spatially registered light transmission apertures 165A1, 165A2 and 165A3 are formed through the bottom panel of the first compartment 162, in spatial registration with the light transmission apertures 29A′, 28′, 29B′ formed in subsystem 25′. Below light transmission apertures 165A1, 165A2 and 165A3, there is formed a completely open light transmission aperture 165B, defined by vertices EFBC, which permits laser light to exit and enter the first compartment 162 during system operation. A hingedly connected panel 169 is provided on the

side opening of the system housing 161, defined by vertices ABCD. The function of this hinged panel 169 is to enable authorized personnel to access the interior of the housing and clean the glass windows provided over light transmission apertures 29A′, 28′, 29B′. This is an important consideration in most industrial scanning environments.

As shown in Figs. 12B, the LDIP subsystem 122 is mounted within the second compartment 164, along with beam folding mirror 163 directed towards a second light transmission aperture 166 formed in the bottom panel of the second compartment 164, in an optically-isolated manner from the first set of light transmission apertures 165A1, 165A2 and 165A3. The function of the beam folding mirror 163 is to enable the LDIP subsystem 122 to project its dual, angularly-spaced amplitude-modulated (AM) laser beams 167A/167B out of its housing, off beam folding mirror 163, and towards a target object to be dimensioned and profiled in accordance with the principles of invention detailed in copending US Application No. 09/327,756 filed June 7, 1999, supra, and International PCT Application No. PCT/US00/15624, supra. Also, this light transmission aperture 166 enables reflected laser return light to be collected and detected off the illuminated target object.

As shown in Fig. 12B, a stationary cylindrical lens array 299 is mounted in front of each PLIA (6A, 6B) adjacent the illumination window formed within the optics bench 8 of the PLIIM-based subsystem 25′. The function performed by cylindrical lens array 299 is to optically combine the individual PLIB components produced from the PLIMs constituting the PLIA, and project the combined PLIB components onto points along the surface of the object being illuminated. By virtue of this inventive feature, each point on the object surface being imaged will be illuminated by different sources of laser illumination located at different points in space (i.e. spatially coherent-reduced laser illumination), thereby reducing the RMS power of speckle-pattern noise observable at the linear image detection array of the PLIIM-based subsystem.

As shown in Fig. 12C, various optical and electro-optical components associated with the unitary package dimensioning and identification system of Fig. 9 are mounted on a first optical bench 510 that is installed within the first optically-isolated cavity 162 of the system housing. As shown, these components include: the camera subsystem 3″, its variable zoom and focus lens assembly, electric motors for driving the linear lens transport carriages associated with this subsystem, and the microcomputer for realizing the camera control computer 22; camera FOV folding mirror 9, power supplies; VLD racks 6A and 6B associated with the PLIAs of the system; microcomputer 512 employed in the LDIP subsystem 122; the microcomputer for realizing the camera control computer 22 and image processing computer 21; connectors, and the like.

As shown in Fig. 12D, various optical and electro-optical components associated with the unitary package dimensioning and identification system of Fig. 9 are mounted on a second

optical bench 520 that is installed within the second optically-isolated cavity 164 of the system housing. As shown, these components include, for the LDIP subsystem 122: a pair of VLDs 521A and 521B for producing a pair of AM laser beams 167A and 167B for use by the subsystem; a motor-driven rotating polygon structure 522 for sweeping the pair of AM laser beams across the rotating polygon 522; a beam folding mirror 163 for folding the swept AM laser beams and directing the same out into the scanning field of the subsystem at different scanning angles, so enable the scanning of packages and other objects within its scanning field via AM laser beams 167A/167B; a first collector mirror 523 for collecting AM laser light reflected off a package scanned by the first AM laser beam, and first light focusing lens 524 for focusing this collected laser light to a first focal point; a first avalanche-type photo-detector 525 for detecting received laser light focused to the first focal point, and generating a first electrical signal corresponding to the received AM laser beam detected by the first avalanche-type photo-detector 525; a second collector mirror 526 for collecting AM laser light reflected off the package scanned by the second AM laser beam, and a second light focusing lens 527 for focusing collected laser light to a second focal point; a second avalanche-type photo-detector 528 for detecting received laser light focused to the second focal point, and generating a second electrical signal corresponding to the received AM laser beam detected by the second avalanche-type photo-detector 528; and a microcontroller and storage memory (e.g. hard-drive) 529 which, in cooperation with LDIP computer 512, provides the computing platform used in the LDIP subsystem 122 for carrying out the image processing, detection and dimensioning operations performed thereby. For further details concerning the LDIP subsystem 122, and its digital image processing operations, reference should be made to copending US Application No. 09/327,756 filed June 7, 1999, supra, and International PCT Application No. PCT/US00/15624, supra.

As shown in Fig. 12E, the IFD subsystem 3" employed in unitary system 120 comprises: a stationary lens system 530 mounted before the stationary linear (CCD-type) image detection array 3A; a first movable lens system 531 for stepped movement relative to the stationary lens system during image zooming operations; and a second movable lens system 532 for stepped movements relative to the first movable lens system 531 and the stationary lens system 530 during image focusing operations. Notably, such variable zoom and focus capabilities that are driven by lens group translators 533 and 534, respectively, operate under the control of the camera control computer 22 in response to package height, length, width, velocity and range intensity information produced in real-time by the LDIP subsystem 122. The IFD (i.e. camera) subsystem 3" of the illustrative embodiment will be described in greater detail hereinafter with reference to the tables and graphs shown in Fig. 21, 22 and 23.

In Figs. 13A through 13C, there is shown an alternative system housing design 540 for use with the unitary package identification and dimensioning subsystem of the present invention. As shown, the housing 540 has the same light transmission apertures of the housing design shown in Figs. 12A and 12B, but has no housing panels disposed about the light transmission apertures 541A, 541B and 542, through which planar laser illumination beams (PLIBs) and the field of view (FOV) of the PLIIM-based subsystem extend, respectively. This feature of the present invention provides a region of space (i.e. housing recess) into which an optional device (not shown) can be mounted for carrying out a speckle-noise reduction solution within a compact box that fits within said housing recess, in accordance with the principles of the present invention. Light transmission aperture 543 enables the AM laser beams 167A/167B from the LDIP subsystem 122 to project out from the housing. Figs. 13B and 13C provide different perspective views of this alternative housing design.

In Fig. 14, the system architecture of the unitary (PLIIM-based) package dimensioning and identification system 120 is shown in greater detail. As shown therein, the LDIP subsystem 122 embodied therein comprises: a Real-Time Package Height Profiling And Edge Detection Processing Module 550; and an LDIP Package Dimensioner 551 provided with an integrated package velocity deletion module that computes the velocity of transported packages based on package range (i.e. height) data maps produced by the front end of the LDIP subsystem 122, as taught in greater detail in copending US Application No. US Application No. 09/327,756 filed June 7, 1999, and International Application No. PCT/US00/15624, filed June 7, 2000, published by WIPO on December 14, 2000 under WIPO No. WO 00/75856 incorporated herein by reference in its entirety. The function of Real-Time Package Height Profiling And Edge Detection Processing Module 550 is to automatically process raw data received by the LDIP subsystem 122 and generate, as output, time-stamped data sets that are transmitted to the camera control computer 22. In turn, the camera control computer 22 automatically processes the received time-stamped data sets and generates real-time camera control signals that drive the focus and zoom lens group translators within a high-speed auto-focus/auto-zoom digital camera subsystem (i.e. the IFD module) 3" so that the image grabber 19 employed therein automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (dpi) independent of package height or velocity. These digital images are then provided to the image processing computer 21 for various types of image processing described in detail hereinabove.

Fig. 15 sets forth a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Height Profiling And Edge Detection Processing Module 550 within LDIP subsystem 122 employed in the PLIIM-based system 120.

As illustrated at Block A in Fig. 15, a row of raw range data collected by the LDIP subsystem 122 is sampled every 5 milliseconds, and time-stamped when received by the Real-Time Package Height Profiling And Edge Detection Processing Module 550.

As indicated at Block B, the Real-Time Package Height Profiling And Edge Detection Processing Module 550 converts the raw data set into range profile data R=f (int. phase), referenced with respect to a polar coordinate system symbolically embedded in the LDIP subsystem 122, as shown in Fig. 17.

At Block C, the Real-Time Package Height Profiling And Edge Detection Processing Module 550 uses geometric transformations (described at Block C) to convert the range profile data set R[i] into a height profile data set h[i] and a position data set x[i].

At Block D, the Real-Time Package Height Profiling And Edge Detection Processing Module 550 obtains current package height data values by finding the prevailing height using package edge detection without filtering, as taught in the method of Fig. 16.

At Block E, the Real-Time Package Height Profiling And Edge Detection Processing Module 550 finds the coordinates of the left and right package edges (LPE, RPE) by searching for the closest coordinates from the edges of the conveyor belt (X_a, X_b) towards the center thereof.

At Block F, the Real-Time Package Height Profiling And Edge Detection Processing Module 550 analyzes the data values {R(nT)} and determines the X coordinate position range $X_{\Delta 1}$, $X_{\Delta 2}$ (measured in R global) where the range intensity changes (i) within the spatial bounds (X_{LPE}, X_{RPE}), and (ii) beyond predetermined range intensity data thresholds.

At Block G in Fig. 15, the Real-Time Package Height Profiling And Edge Detection Processing Module 550 creates a time-stamped data set {X_{LPE}, h, X_{RPE}, V_B, nT} by assembling the following six (6) information elements, namely: the coordinate of the left package edge (LPE); the current height value of the package (h); the coordinate of the right package edge (RPE); X coordinate subrange where height values exhibit maximum intensity changes and the height values within said subrange; package velocity (V_b); and the time-stamp (nT). Notably, the belt/package velocity measure V_b is computed by the LDIP Package Dimensioner 551 within LDIP Subsystem 122, and employs integrated velocity detection techniques described in copending US Application No. US Application No. 09/327,756 filed June 7, 1999, and International Application No. PCT/US00/15624, filed June 7, 2000, published by WIPO on December 14, 2000 under WIPO No. WO 00/75856 incorporated herein by reference in its entirety.

Thereafter, at Block H in Fig. 15, the Real-Time Package Height Profiling And Edge Detection Processing Module 550 transmits the assembled (hextuple) data set to the camera control computer 22 for processing and subsequent generation of real-time camera control

signals that are transmitted to the Auto-Focus/Auto-Zoom Digital Camera Subsystem 3''. These operation will be described in greater detail hereinafter.

Fig. 16 sets forth a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Edge Detection Processing Method which is performed by the Real-Time Package Height Profiling And Edge Detection Processing Module 550 at Block D in Fig. 15. This routine is carried out each time a new raw range data set is received by the Real-Time Package Height Profiling And Edge Detection Processing Module, which occurs at a rate of about every 5 milliseconds or so in the illustrative embodiment. Understandably, this processing time may be lengthened and shortened as the applications at hand may require.

As shown at Block A in Fig. 16, this module commences by setting (i) the default value for x coordinate of the left package edge X_{LPE} equal to the x coordinate of the left edge pixel of the conveyor belt, and (ii) the default pixel index i equal to location of left edge pixel of the conveyor belt I_a. As indicated at Block B, the module sets (i) the default value for the x coordinate of the right package edge X_{RPE} equal to the x coordinate of the right edge pixel of the conveyor belt I_b, and (ii) the default pixel index i equal to the location of the right edge pixel of the conveyor belt I_b.

At Block C in Fig. 16, the module determines whether the search for left edge of the package reached the right edge of the belt (I_b) minus the search (i.e. detection) window size WIN. Notably, the size of the WIN parameter is set on the basis of the noise level present within the captured image data.

At Block D in Fig. 16, the module verifies whether the pixels within the search window satisfy the height threshold parameter, Hthres. In the illustrative embodiment, the height threshold parameter Hthres is set on the basis of a percentage of the expected package height of the packages, although it is understood that more complex height thresholding techniques can be used to improve performance of the method, as may be required by particular applications.

At Block E in Fig. 16, the module verifies whether the pixels within the search window are located to the right of the left belt edge.

At Block F in Fig. 16, the module slides the search window one (1) pixel location to the right direction.

At Block G in Fig. 16, the module sets: (i) the x-coordinate of the left edge of the package to equal the x-coordinate of the left most pixel in the search window WIN; (ii) the default x-coordinate of the package's right edge equal to the x-coordinate of the belt's right edge; and (iii) the default pixel location of the package's right edge equal to the pixel location of the belt's right edge.

At Block H in Fig. 16, the module verifies whether the search for right package edge reached the left edge of the belt, minus the size of the search window WIN.

At Block I in Fig. 16, the module verifies whether the pixels within search window WIN satisfy the height threshold Hthres.

As Block J in Fig. 16, the module verifies whether the pixels within search window are located to the left of the belt's right edge.

At Block K in Fig. 16, the module sides the search window one (1) pixel location to the left direction.

At Block L in Fig. 16, the module sets the RIGHT package x-coordinate to the x-coordinate of the right most pixel in the search window.

At Block M in Fig. 16, the package edge detection process is completed. The variables LPE and RPE (i.e. stored in its memory locations) contain the x coordinates of the left and right edges of the detected package. These coordinate values are returned to the process at Block D in the flow chart of Fig. 15.

Notably, the processes and operations specified in Figs. 15 and 16 are carried out for each sampled row of raw data collected by the LDIP subsystem 122, and therefore, do not rely on the results computed by the computational-based package dimensioning processes carried out in the LDIP subsystem 122, described in great detail in copending US Application No. 09/327,756 filed June 7, 1999, and incorporated herein reference in its entirety. This inventive feature enables ultra-fast response time during control of the camera subsystem.

As will be described in greater detail hereinafter, the camera control computer 22 controls the auto-focus/auto-zoom digital camera subsystem 3″ in an intelligent manner using the real-time camera control process illustrated in Figs. 18A and 18B. A particularly important inventive feature of this camera process is that it only needs to operate on one data set at time a time, obtained from the LDIP Subsystem 122, in order to perform its complex array of functions. Referring to Figs. 18A and 18B, the real-time camera control process of the illustrative embodiment will now be described with reference to the data structures illustrated in Figs. 19 and 20, and the data tables illustrated in Figs. 21 and 23.

Real-Time Camera Control Process Of The Present Invention

In the illustrative embodiment, the Real-time Camera Control Process 560 illustrated in Figs. 18A and 18B is carried out within the camera control computer 21 of the PLIIM-based system 120 shown in Fig. 9. It is understood, however, that this control process can be carried out within any of the PLIIM-based systems disclosed herein, wherein there is a need to perform automated real-time object detection, dimensioning and identification operations.

This Real-time Camera Control Process provides each PLIIM-based camera subsystem of the present invention with the ability to intelligently zoom in and focus upon only the surfaces

of a detected object (e.g. package) which might bear object identifying and/or characterizing information that can be reliably captured and utilized by the system or network within which the camera subsystem is installed. This inventive feature of the present invention significantly reduces the amount of image data captured by the system which does not contain relevant information. In turn, this increases the package identification performance of the camera subsystem, while using less computational resources, thereby allowing the camera subsystem to perform more efficiently and productivity.

As illustrated in Figs. 18A and 18B, the camera control process of the present invention has multiple control threads that are carried out simultaneously during each data processing cycle (i.e. each time a new data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550 within the LDIP subsystem 122). As illustrated in this flow chart, the data elements contained in each received data set are automatically processed within the camera control computer in the manner described in the flow chart, and at the end of each data set processing cycle, generates real-time camera control signals that drive the zoom and focus lens group translators powered by high-speed motors and quick-response linkage provided within high-speed auto-focus/auto-zoom digital camera subsystem (i.e. the IFD module) 3" so that the camera subsystem 3" automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity. Details of this control process will be described below.

As indicated at Block A in Fig. 18A, the camera control computer 22 receives a time-stamped hextuple data set from the LDIP subsystem 122 after each scan cycle completed by AM laser beams 167A and 167B. In the illustrative embodiment, this data set contains the following data elements: the coordinate of the left package edge (LPE); the current height value of the package (h); x coordinate subrange , and exhibit maximum intensity changes or variations (e.g. indicative of text or other graphic information markings) and the height values contained within said subrange; the coordinate of the right package edge (RPE); package velocity (V_b); and the time-stamp (nT). The data elements associated with each current data set are initially buffered in an input row (i.e. Row 1) of the Package Data Buffer illustrated in Fig. 19. Notably, the Package Data Buffer shown in Fig. 19 functions like a six column first-in-first-out (FIFO) data element queue. As shown, each data element in the raw data set is assigned a fixed column index and (variable) row index which increments as the raw data set is shifted one index unit as each new incoming raw data set is received into the Package Data Buffer. In the illustrative embodiment, the Package Data Buffer has M number of rows, sufficient in size to

determine the spatial boundaries of a package scanned by the LDIP subsystem using real-time sampling techniques which will be described in detail below.

As indicated at Block A in Fig. 18A, in response to each Data Set received, the camera control computer 22 also performs the following operations: (i) computes the optical power (measured in milliwatts) which each VLD in the PLIIM-based system 25″ (shown in Figs. 3E1 through 3E8) must produce in order that each digital image captured by the PLIIM-based system will have substantially the same "white" level, regardless of conveyor belt speed; and (2) transmits the computed VLD optical power value(s) to the microcontroller 764 associated with each PLIA in the PLIIM-based system. The primary motivation for capturing images having a substantially the same "white" level is that this information level condition greatly simplifies the software-based image processing operations to be subsequently carried out by the image processing computer subsystem. Notably, the flow chart shown in Figs. 18C1 and 18C2 describes the steps of a method of computing the optical power which must be produced from each VLD in the PLIIM-based system, to ensure the capture of digital images having a substantially uniform "white" level, regardless of conveyor belt speed. This method will be described below.

As indicated at Block A in Fig. 18C1, the camera control computer 22 computes the Line Rate of the linear CCD image detection array (i.e. sensor chip) 3A based on (i) the conveyor belt speed (computed by the LDIP subsystem 122), and (ii) the constant image resolution (i.e. in dots per inch) desired, using the following formula: Line Rate= [Belt Velocity] x[Resolution].

As indicated at Block B in Fig. 18C1, the camera control computer 22 then computes the photo-integration time period of the linear image detection array 3A required to produce digital images having a substantially uniform "white" level, regardless of conveyor belt speed. This step is carried out using the formula: Photo-Integration Time Period=1/Line Rate.

As indicated at Block C in Fig. 18C2, the camera control computer 22 then computes the optical power (e.g. milliwatts) which each VLD in the PLIIM-based system must illuminate in order to produce digital images having a substantially uniform "white" level, regardless of conveyor belt speed. This step is carried out using the formula: VLD Optical Power= Constant/Photo-Integration Time Period.

Once the VLD Optical Power is computed for each VLD in the system, the camera control computer 22 then transmits (i.e. broadcasts) this parameter value, as control data, to each PLIA microcontroller 764 associated with each PLIA, along with a global timing (i.e. synchronization) signal. The PLIA micro-controller 764 uses the global synchronization signal to determine when it should enable its associated VLDs to generate the particular level of optical power indicated by the currently received control data values. When the Optical Power value is received by the microcontroller 764, it automatically converts this value into a set of

digital control signals which are then provided to the digitally-controlled potentimeters (763) associated with the VLDs so that the drive current running through the junction of each VLD is precisely controlled to produce the computed level of optical power to be used to illuminate the object (whose speed was factored into the VLD optical power calculation) during the subsequent image capture operations carried out by the PLIIM-based system.

In accordance with the principles of the present invention, as the speed of the conveyor belt and thus objects transported therealong will vary over time, the camera control process, running the control subroutine set forth in Figs. 18C1 and 18C2, will dynamically program each PLIA microcontroller 764 within the PLIIM-based system so that the VLDs in each PLIA illuminate at optical power levels which ensure that captured digital images will automatically have a substantially uniform "white" level, independent of conveyor belt speed.

Notably, the intensity control method of the present invention described above enables the electronic exposure control (EEC) capability provided on most linear CCD image sensors to be disabled during normal operation so that image sensor's nominal noise pattern, otherwise distorted by the EEC aboard the imager sensor, can be used to perform offset correction on captured image data.

Returning now to Block B in Fig. 18A, the camera control computer 22 analyzes the height data in the Package Data Buffer and detects the occurrence of height discontinuities, and based on such detected height discontinuities, camera control computer 22 determines the corresponding coordinate positions of the leading package edges specified by the left-most and right-most coordinate values (LPE and RPE) contained in the data set in the Package Data Buffer at the which the detected height discontinuity occurred.

At Block C in Fig. 18A, the camera control computer 22 determines the height of the package associated with the leading package edges determined at Block B above.

At Block D in Fig. 18A, at this stage in the control process, the camera control computer 22 analyzes the height values (i.e. coordinates) buffered in the Package Data Buffer, and determines the current "median" height of the package. At this stage of the control process, numerous control "threads" are started, each carrying out a different set of control operations in the process. As indicated in the flow chart of Figs. 18A and 18B, each control thread can only continue when the necessary parameters involved in its operation have been determined (e.g. computed), and thus the control process along a given control thread must wait until all involved parameters are available before resuming its ultimate operation (e.g. computation of a particular intermediate parameter, or generation of a particular control command), before ultimately returning to the start Block A, at which point the next time-stamped data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550. In the illustrative embodiment, such data set input operations are carried out every 5

milliseconds, and therefore updated camera commands are generated and provided to the auto-focus/auto-zoom camera subsystem at substantially the same rate, to achieve real-time adaptive camera control performance required by demanding imaging applications.

As indicated at Blocks E, F, G H, I, A in Figs. 18A and 18B, a first control thread runs from Block D to Block A so as to reposition the focus and zoom lens groups within the auto-focus/auto-zoom digital camera subsystem each time a new data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550.

As indicated at Block E, the camera control computer 22 uses the Focus/Zoom Lens Group Position Lookup Table in Fig. 21 to determine the focus and zoom lens group positions based which will capture focused digital images having constant dpi resolution, independent of detected package height. This operation requires using the median height value determined at Block D, and looking up the corresponding focus and zoom lens group positions listed in the Focus/Zoom Lens Group Position Lookup Table of Fig. 21.

At Block F, the camera control computer 22 transmits the Lens Group Movement translates the focus and zoom lens group positions determined at Block E into Lens Group Movement Commands, which are then transmitted to the lens group position translators employed in the auto-focus/auto-zoom camera subsystem (i.e. IFD Subsystem) 3''.

At Block G, the IFD Subsystem 3'' uses the Lens Group Movement Commands to move the groups of lenses to their target positions within the IFD Subsystem.

Then at Block H, the camera control computer 22 checks the resulting positions achieved by the lens group position translators, responding to the transmitted Lens Group Movement Commands. At Blocks I and J, the camera control computer 22 automatically corrects the lens group positions which are required to capture focused digital images having constant dpi resolution, independent of detected package height. As indicated at by the control loop formed by Blocks H, I, J, H, the camera control computer 22 corrects the lens group positions until focused images are captured with constant dpi resolution, independent of detected package height, and when so achieved, automatically returns this control thread to Block A as shown in Fig. 18A.

As indicated at Blocks D, K, L, M in Figs. 18A and 18B, a second control thread runs from Block D in order to determine and set the optimal photo-integration time period ($\Delta T_{photo\text{-}integration}$) parameter which will ensure that digital images captured by the auto-focus/auto-zoom digital camera subsystem will have pixels of a square geometry (i.e. aspect ratio of 1:1) required by typical image-based bar code symbol decode processors and OCR processors. As indicated at Block K, the camera control computer analyzes the current median height value in the Data Package Buffer, and determines the speed of the package (V_b). At Block L, the camera control computer uses the computed values of average package height, belt speed (V_b) and the Photo-

Integration Time Look-Up Table of Fig. 23, to determine the photo-integration time parameter ($\Delta T_{photo\text{-}integration}$) which will ensure that digital images captured by the auto-focus/auto-zoom digital camera subsystem will have pixels of a square geometry (i.e. aspect ratio of 1:1). At Block M, the camera control computer 22 generates a digital photo-integration time control signal based on the photo-integration time parameter ($\Delta T_{photo\text{-}integration}$) found in the Photo-Integration Time Look-Up Table, and sends this control signal to the CCD image detection array employed in the auto-focus/auto-zoom digital camera subsystem (i.e. the IFD Module). Thereafter, this control thread returns to Block A as indicated in Fig. 18A.

As indicated at Blocks D, N, O, P, R in Figs. 18A and 18B, a third control thread runs from Block D in order to determine the pixel indices (i,j) of a selected portion of a captured image which defines the "region of interest" (ROI) on a package bearing package identifying information (e.g. bar code label, textual information, graphics, etc.), and to use these pixel indices (i,j) to produce image cropping control commands which are sent to the image processing computer 21. In turn, these control commands are used by the image processing computer 21 to crop pixels in the ROI of captured images, transferred to image processing computer 21 for image-based bar code symbol decoding and/or OCR-based image processing. This ROI cropping function serves to selectively identify for image processing only those image pixels within the Camera Pixel Buffer of Fig. 20 having pixel indices (i,j) which spatially correspond to the (row,column) indices in the Package Data Buffer of Fig. 19.

As indicated at Block N in Fig. 18A, the camera control computer transforms the position of left and right package edge (LPE, RPE) coordinates (buffered in the row the Package Data Buffer at which the height value was found at Block D), from the local Cartesian coordinate reference system symbolically embedded within the LDIP subsystem shown in Fig. 17, to a global Cartesian coordinate reference system R_{global} embedded, for example, within the center of the conveyor belt structure, beneath the LDIP subsystem 122, in the illustrative embodiment. Such coordinate frame conversions can be carried out using homogeneous transformations (HG) well known in the art.

At Block O in Fig. 18B, the camera control computer detects the x coordinates of the package boundaries based on the spatially transformed coordinate values of the left and right package edges (LPE,RPE) buffered in the Package Data Buffer, shown in Fig. 19.

At Block P in Fig. 18B, the camera control computer 22 determines the corresponding pixel indices (i,j) which specifies the portion of the image frame (i.e. a slice of the region of interest), to be effectively cropped from the image to be subsequently captured by the auto-focus/auto-zoom digital camera subsystem 3". This pixel indices specification operation involves using (i) the x coordinates of the detected package boundaries determined at Block O,

and (ii) optionally, the subrange of x coordinates bounded within said detected package boundaries, over which maximum range "intensity" data variations have been detected by the module of Fig. 15. By using the x coordinate boundary information specified in item (i) above, the camera control computer 22 can determine which image pixels represent the overall detected package, whereas when using the x coordinate subrange information specified in item (ii) above, the camera control computer 22 can further determine which image pixels represent a bar code symbol label, hand-writing, typing, or other graphical indicia recorded on the surface of the detected package. Such additional information enables the camera control computer 22 to selectively crop only pixels representative of such information content, and inform the image processing computer 21 thereof, on a real-time scanline-by-scanline basis, thereby reducing the computational load on image processing computer 21 by use of such intelligent control operations.

Thereafter, this control thread dwells at Block R in Fig. 18B until the other control threads terminating at Block Q have been executed, providing the necessary information to complete the operation specified at Block Q, and then proceed to Block R, as shown in Fig. 18B.

As indicated at Block Q in Fig. 18B, the camera control computer uses the package time stamp (nT) contained in the data set being currently processed by the camera control computer, as well as the package velocity (V_b) determined at Block K, to determine the "Start Time" of Image Frame Capture (STIC). The reference time is established by the package time stamp (nT). The Start Time when the image frame capture should begin is measured from the reference time, and is determined by (1) predetermining the distance Δz measured between (i) the local coordinate reference frame embedded in the LDIP subsystem and (ii) the local coordinate reference frame embedded within the auto-focus/auto-zoom camera subsystem, and dividing this predetermined (constant) distance measure by the package velocity (V_b). Then at Block R, the camera control computer 22 (i) uses the Start Time of Image Frame Capture determined at Block Q to generate a command for starting image frame capture, and (ii) uses the pixel indices (i,j) determined at Block P to generate commands for cropping the corresponding slice (i.e. section) of the region of interest in the image to be or being captured and buffered in the Image Buffer within the IFD Subsystem (i.e. auto-focus/auto-zoom digital camera subsystem).

Then at Block S, these real-time "image-cropping" commands are transmitted to the IFD Subsystem (auto-focus/auto-zoom digital camera subsystem) 3" and the control process returns to Block A to begin processing another incoming data set received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550. This aspect of the inventive camera control process 560 effectively informs the image processing computer 21 to only process those cropped image pixels which the LDIP subsystem 122 has determined as

representing graphical indicia containing information about either the identity, origin and/or destination of the package moving along the conveyor belt.

Alternatively, camera control computer 22 can use computed ROI pixel information to crop pixel data in captured images in camera control computer 22 and then transfer such cropped images to the image processing computer 21 for processing.

Also, any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the unitary system 120 to provide an ultra-compact, ultra-lightweight system capable of high performance image acquisition and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using solid-state VLD devices, as taught herein.

Second Illustrative Embodiment Of The Unitary Package Identification And Dimensioning System Of The Present Invention Embodying A PLIIM-Based Subsystem Of The Present Invention And A LADAR-Based Imaging, Detecting And Dimensioning Subsystem

Referring now to Figs. 24, 25, and 26, a unitary PLIIM-based package identification and dimensioning system of the second illustrated embodiment, indicated by reference numeral 140, will now be described in detail.

As shown in Fig. 24, the unitary PLIIM-based system 140 comprises an integration of subsystems, contained within a single housing of compact construction supported above the conveyor belt of a high-speed conveyor subsystem 121, by way of a support frame or like structure. In the illustrative embodiment, the conveyor subsystem 141 has a conveyor belt width of at least 48 inches to support one or more package transport lanes along the conveyor belt. As shown in Fig. 25, the unitary PLIIM-based system 140 comprises four primary subsystem components, namely: (1) a LADAR-based package imaging, detecting and dimensioning subsystem 122 capable of collecting range data from objects on the conveyor belt using a pair of multi-wavelength (i.e. containing visible and IR spectral components) laser scanning beams projected at different angular spacing as taught in copending US Application No. 09/327,756 filed June 7, 1999, supra, and International PCT Application No. PCT/US00/15624 filed December 7, 2000, incorporated herein by reference; (2) a PLIIM-based bar code symbol reading subsystem 25", shown in Figs. 6D1 through 6D5, for producing a 3-D scanning volume above the conveyor belt, for scanning bar codes on packages transported therealong; (3) an input/output subsystem 127 for managing the inputs to and outputs from the unitary system; a network controller 132 for connecting to a local or wide area IP network, and support one or more networking protocols, such as, for example, Ethernet, Appletalk, etc.; a high-speed fiber optic (FO) network controller 133 for connecting the subsystem 140 to a local or

wide area IP network and supporting one or more networking protocols such as, for example, Ethernet, Appletalk, etc.; and (4) a data management computer 129 with a graphical user interface (GUI) 130, for realizing a data element queuing, handling and processing subsystem 131, as well as other data and system management functions. As shown in Fig. 25, the package imaging, detecting and dimensioning subsystem 122 embodied within system 140 comprises the same integration of subsystems as shown in Fig. 10, and thus warrants no further discussion. It is understood, however, that other non-LADAR based package detection, imaging and dimensioning subsystems could be used to emulate the functionalities of the LDIP subsystem 122.

As shown in Fig. 25, system 140 comprises a PLIIM-based camera subsystem 25''' which includes a high-resolution 2D CCD camera subsystem 25'' similar in many ways to the subsystem shown in Figs. 6D1 through 6E3, except that the 2-D CCD camera's 3-D field of view is automatically steered over a large scanning field, as shown in Fig. 6E4, in response to FOV steering control signals automatically generated by the camera control computer 22 as a low-resolution CCD area-type camera (640x640 pixels) 61 determines the x,y position coordinates of bar code labels on scanned packages. As shown in Figs. 5B3, 5C3, 6B3, and 6C3, the components (61A, 61B and 62) associated with low-resolution CCD area-type camera 61 are easily integrated within the system architecture of PLIIM-based camera subsystems. In the illustrative embodiment, low-resolution camera 61 is controlled by a camera control process carried out within the camera control computer 22, by modifying the camera control process illustrated in Figs. 18A and 18B. The major difference with this modified camera control process is that it will include subprocesses that generate FOV steering control signals, in addition to zoom and focus control signals, discussed in great detail hereinabove.

In the illustrative embodiment, when the low-resolution CCD image detection array 61A detects a bar code symbol on a package label, the camera control computer 22 automatically (i) triggers into operation a high-resolution CCD image detector 55A and the planar laser illumination arrays (PLIA) 6A and 6B operably associated therewith, and (ii) generates FOV steering control signals for steering the FOV of camera subsystem 55''' and capturing 2-D images of packages within the 3-D field of view of the high-resolution image detection array 61A. The zoom and focal distance of the imaging subsystem employed in the high-resolution camera (i.e. IFD module) 55''' are automatically controlled by the camera control process running within the camera control computer 22 using, for example, package height coordinate and velocity information acquired by the LDIP subsystem 122. High-resolution image frames (i.e. scan data) captured by the 2-D image detector 55A are then provided to the image processing computer 21 for decode processing of bar code symbols on the detected package

label, or OCR processing of textual information represented therein. In all other respects, the PLIIM-based system 140 shown in Fig. 24 is similar to PLIIM-based system 120 shown in Fig. 9. By embodying PLIIM-based camera subsystem 25″ and LDIP package detecting and dimensioning subsystem 122 within a single housing 141, an ultra-compact device is provided that uses a low-resolution CCD imaging device to detect package labels and dimension, identify and track packages moving along the package conveyor, and then uses such detected label information to activate a high-resolution CCD imaging device to acquire high-resolution images of the detected label for high performance decode-based image processing.

Notably, any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the unitary system 140 to provide an ultra-compact, ultra-lightweight system capable of high performance image acquisition and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using coherent radiation.

<u>Tunnel-Type Package Identification And Dimensioning System Of The Present Invention</u>

The PLIIM-based package identification and dimensioning systems and subsystems described hereinabove can be configured as building blocks to build more complex, more robust systems designed for diverse types of object identification and dimensioning applications. In Fig. 27, there is shown a four-sided tunnel-type package identification and dimensioning system 570 that has been constructed by arranging, about a high-speed package conveyor belt subsystem 571, four PLIIM-based package identification (PID) units 120 of the type shown in Figs. 13A through 26, and integrating these PID units within a high-speed data communications network 572 having a suitable network topology and configuration, as illustrated, for example, in Figs. 28 and 29.

In this illustrative tunnel-type system, only the top PID unit 120 includes LDIP subsystem 122, as this unit functions as a master PID unit within the tunnel system, whereas the side and bottom PID units 120 are not provided with a LDIP subsystem 122 and function as slave PID units. As such, the side and bottom PID units 120′ are programmed to receive package dimension data (e.g. height, length and width coordinates) from the master PID unit 120 on a real-time basis, and automatically convert (i.e. transform) these package dimension coordinates into their local coordinate reference frames in order to use the same to dynamically control the zoom and focus parameters of the camera subsystems employed in the tunnel system. This centralized method of package dimensioning offers numerous advantages over prior art systems and will be described in greater detail with reference to Figs. 30 through 32B.

As shown in Fig. 27, the camera field of view (FOV) of the bottom PID unit 120′ of the tunnel system 570 is arranged to view packages through a small gap 573 provided between conveyor belt sections 571A and 571B. Notably, this arrangement is permissible by virtue of the fact that the camera's FOV and its coplanar PLIB jointly have thickness dimensions on the order of millimeters. As shown in Fig. 28, all of the PID units in the tunnel system are operably connected to an Ethernet control hub 575 (ideally contained in one of the slave PID units) associated with a local area network (LAN) embodied within the tunnel system. As shown, an external tachometer (i.e. encoder) 576 connected to the conveyor belt 571 provides tachometer input signals to each slave unit 120 and master unit 120, as a backup to integrated velocity detector provided within the LDIP subsystem 122. This is an optional feature which may have advantages in environments where the belt speed fluctuates frequently and by significant amounts. Fig. 28 shows the tunnel-based system of Fig. 27 embedded within a first-type LAN having an Ethernet control hub 575, for communicating data packets to control the operation of units 120 in the LAN, but not transfer camera data (e.g. 80 megabytes/sec).

Fig. 29 shows the tunnel system of Fig. 27 embedded within a second-type LAN having a Ethernet control hub 575 and a Ethernet data switch 577, and an encoder 576. The function of the Ethernet data switch 577 is to transfer data packets relating to camera data output, whereas the functions of control hub 575 are the same as in the tunnel network system configuration of Fig. 28. The advantages of using the tunnel network configuration of Fig. 29 is that camera data can be transferred over the LAN, and when using fiber optical (FO) cable, camera data can be transferred very long distances over FO-cable using the Ethernet networking protocol (i.e. Ethernet over fiber). As discussed hereinabove, the advantage of using Ethernet over fiber optical cable is that a "keying" workstation 580 can be located thousands of feet away from the tunnel system 570 within a package routing facility, without compromising camera data integrity due to transmission loss and/or errors.

Real-Time Package Coordinate Data Driven Method Of Camera Zoom And Focus Control In Accordance With The Principles Of The Present Invention

In Figs. 30 through 32B, CCD camera-based tunnel system 570 of Fig. 27 is schematically illustrated employing a real-time method of automatic camera zoom and focus control in accordance with the principles of the present invention. As will be described in greater detail below, this real-time method is driven by package coordinate data and involves (i) dimensioning packages in a global coordinate reference system, (ii) producing package coordinate data referenced to said global coordinate reference system, and (iii) distributing said package coordinate data to local coordinate references frames in the system for conversion of

said package coordinate data to local coordinate reference frames and subsequent use automatic camera zoom and focus control operations upon said packages. This method of the present invention will now be described in greater detail below using the four-sided tunnel-based system 570 of Fig. 27, described above.

As shown in Fig. 30, the four-sided tunnel-type camera-based package identification and dimensioning system of Fig. 27 comprises: a single master PID unit 120 embodying a LDIP subsystem 122, mounted above the conveyor belt structure 571; three slave PID units 120′, 120′ and 120′, mounted on the sides and bottom of the conveyor belt; and a high-speed data communications network 572 supporting a network protocol such as, for example, Ethernet, and enabling high-speed packet-type data communications among the four PID units within the system. As shown, each PID unit is connected to the network communication medium of the network through its network controller 132 (133) in a manner well known in the computer networking arts.

As schematically illustrated in Figs. 30 and 31, local coordinate reference systems are symbolically embodied within each of the PID units deployed in the tunnel-type system of Fig. 27, namely: local coordinate reference system R_{local0} symbolically embodied within the master PID unit 120; local coordinate reference system R_{local1} symbolically embodied within the first side PID unit 120′; local coordinate reference system R_{local2} symbolically embodied within the second side PID unit 120′; and local coordinate reference system R_{local3} symbolically embodied within the bottom PID unit 120′. In turn, each of these local coordinate reference systems is "referenced" with respect to a global coordinate reference system R_{global} symbolically embodied within the conveyor belt structure. Package coordinate information specified (by vectors) in the global coordinate reference system can be readily converted to package coordinate information specified in any local coordinate reference system by way of a homogeneous transformation (HG) constructed for the global and the particular local coordinate reference system. Each homogeneous transformation can be constructed by specifying the point of origin and orientation of the x,y,z axes of the local coordinate reference system with respect to the point of origin and orientation of the x,y,z axes of the global coordinate reference system. Such details on homogeneous transformations are well known in the art.

To facilitate construction of each such homogeneous transformation between a particular local coordinate reference system (symbolically embedded within a particular slave PID unit 120′) and the global coordinate reference system (symbolically embedded within the master PID unit 120), the present invention further provides a novel method of and apparatus for measuring, in the field, the pitch and yaw angles of each slave PID unit 120′ in the tunnel system, as well as the elevation (i.e. height) of the PID unit, that is relative to the local coordinate reference frame symbolically embedded within the local PID unit. In the illustrative

embodiment, shown in Fig. 31A, such apparatus is realized in the form of two different angle-measurement (e.g. protractor) devices 2500A and 2500B integrated within the structure of each slave and master PID housing and the support structure provided to support the same within the tunnel system. The purpose of such apparatus is to enable the taking of such field measurements (i.e. angle and height readings) so that the precise coordinate location of each local coordinate reference frame (symbolically embedded within each PID unit) can be precisely determined, relative to the master PID unit 120. Such coordinate information is then used to construct a set of "homogeneous transformations" which are used to convert globally acquired package dimension data at each local coordinate frame, into locally referenced package dimension data. In the illustrative embodiment, the master PID unit 120 is provided with an LDIP subsystem 122 for acquiring package dimension information on a real-time basis, and such information is broadcasted to each of the slave PID units 120′ employed within the tunnel system. By providing such package dimension information to each PID unit in the system, and converting such information to the local coordinate reference system of each such PID unit, the optical parameters of the camera subsystem within each local PID unit are accurately controlled by its camera control computer 22 using such locally-referenced package dimension information, as will be described in greater detail below.

As illustrated in Fig. 31A, each angle measurement device 2500A and 2500B is integrated into the structure of the PID unit 120′ (120) by providing a pointer or indicating structure (e.g. arrow) 2501A (2501B) on the surface of the housing of the PID unit, while mounting angle-measurement indicator 2503A (2503A) on the corresponding support structure 2504A (2400B) used to support the housing above the conveyor belt of the tunnel system. With this arrangement, to read the pitch or yaw angle, the technician only needs to see where the pointer 2501A (or 2501B) points against the angle-measurement indicator 2503A (2503B), and then visually determine the angle measure at that location which is the angle measurement to be recorded for the particular PID unit under analysis. As the position and orientation of each angle-measurement indicator 2503A (2503B) will be precisely mounted (e.g. welded) in place relative to the entire support system associated with the tunnel system, PID unit angle readings made against these indicators will be highly accurate and utilizable in computing the homogeneous transformations (e.g. during the set-up and calibration stage) and carried out at each slave PID unit 120′ and possibly the master PID unit 120 if the LDIP subsystem 122 is not located within the master PID unit, which may be the case in some tunnel installations. To measure the elevation of each PID unit 120′ (or 120), an arrow-like pointer 2501C is provided on the PID unit housing and is read against an elevation indicator 2503C mounted on one of the support structures.

Once the PID units have been installed within a given tunnel system, such information must be ascertained to (i) properly construct the homogeneous transformation expression between each local coordinate reference system and the global coordinate reference system, and (ii) subsequently program this mathematical construction within camera control computer 22 within each PID unit 120 (120'). Preferably, a PID unit support framework installed about the conveyor belt structure, can be used in the tunnel system to simplify installation and configuration of the PID units at particular predetermined locations and orientations required by the scanning application at hand. In accordance with such a method, the predetermined location and orientation position of each PID unit can be premarked or bar coded. Then, once a particular PID unit has been installed, the location/orientation information of the PID unit can be quickly read in the field and programmed into the camera control computer 22 of each PID unit so that its homogeneous transformation (HG) expression can be readily constructed and programmed into the camera control compute for use during tunnel system operation. Notably, a hand-held bar code symbol reader, operably connected to the master PID unit, can be used in the field to quickly and accurately collect such unit position/orientation information (e.g. by reading bar code symbols pre-encoded with unit position/orientation information) and transmit the same to the master PID unit.

In addition, Fig. 30 illustrates that the LDIP subsystem 122 within the master unit 120 generates (i) package height, width, and length coordinate data and (ii) velocity data, referenced with respect to the global coordinate reference system R_{global}. These package dimension data elements are transmitted to each slave PID unit 120' on the data communication network, and once received, its camera control computer 22 converts there values into package height, width, and length coordinates referenced to its local coordinate reference system using its preprogrammable homogeneous transformation. The camera control computer 22 in each slave PID unit 120 uses the converted package dimension coordinates to generate real-time camera control signals which automatically drive its camera's automatic zoom and focus imaging optics in an intelligent, real-time manner in accordance with the principles of the present invention. The package identification data elements generated by the slave PID unit are automatically transmitted to the master PID unit 120 for time-stamping, queuing, and processing to ensure accurate package dimension and identification data element linking operations in accordance with the principles of the present invention.

Referring to Figs. 32A and 32B, the package-coordinate driven camera control method of the present invention will now be described in detail.

As indicated at Block A in Fig. 32A, Step A of the camera control method involves the master PID unit (with LDIP subsystem 122) generating a package dimension data element (e.g. containing height, width, length and velocity data $\{H,W,L,V\}_G$) for each package transported

through tunnel system, and then using the system's data communications network, to transmit such package dimension data to each slave PID unit downstream the conveyor belt. Preferably, the coordinate information contained in each package dimension data element is referenced with respect to global coordinate reference system R_{global}, although it is understood that the local coordinate reference frame of the master PID unit may also be used as a central coordinate reference system in accordance with the principles of the present invention.

As indicated at Block B in Fig. 32A, Step B of the camera control method involves each slave unit receiving the transmitted package height, width and length data $\{H,W,L,V\}_G$ and converting this coordinate information into the slave unit's local coordinate reference system $R_{local\ i}$, $\{H,W,L,V\}_i$.

As indicated at Block C in Fig. 32A, Step C of the camera control method involves the camera control computer in each slave unit using the converted package height, width, length data $\{H,W,L\}_i$ and package velocity data to generate camera control signals for driving the camera subsystem in the slave unit to zoom and focus in on the transported package as it moves by the slave unit, while ensuring that captured images having substantially constant d.p.i. resolution and 1:1 aspect ratio.

As indicated at Block D in Fig. 32B, Step D of the camera control method involves each slave unit capturing images acquired by its intelligently controlled camera subsystem, buffering the same, and processing the images so as to decode bar code symbol identifiers represented in said images, and/or to perform optical character recognition (OCR) thereupon.

As indicated at Block E in Fig. 32B, Step E of the camera control method involves the slave unit, which decoded a bar code symbol in a processed image, to automatically transmit a package identification data element (containing symbol character data representative of the decoded bar code symbol) to the master unit (or other designated system control unit employing data element management functionalities) for package data element processing.

As indicated at Block F in Fig. 32B, Step F of the camera control method involves the master unit time-stamping each received package identification data element, placing said data element in a data queue, and processing package identification data elements and time-stamped package dimension data elements in said queue so as to link each package identification data element with one said corresponding package dimension data element.

The real-time camera zoom and focus control process described above has the advantage of requiring on only one package detection and dimensioning subsystem, yet enabling (i) intelligent zoom and focus control within each camera subsystem in the system, and (ii) precise cropping of "regions of interest" (ROI) in captured images. Such inventive features enable intelligent filtering and processing of image data streams and thus substantially reduce data processing requirements in the system.

Bioptical PLIIM-Based Product Dimensioning, Analysis And Identification System Of The First Illustrative Embodiment Of The Present Invention

The numerous types of PLIIM-based camera systems disclosed hereinabove can be used as stand-alone devices, as well as components within resultant systems designed to carry out particular functions.

As shown in Figs. 33A through 33C, a pair of PLIIM-based package identification (PID) systems 25′ of Figs. 3E4 through 3E8 are modified and arranged within a compact POS housing 581 having bottom and side light transmission apertures 582 and 583 (beneath bottom and side imaging windows 584 and 585, respectively), to produce a bioptical PLIIM-based product identification, dimensioning and analysis (PIDA) system 580 according to a first illustrative embodiment of the present invention. As shown in Fig. 33C, the bioptical PIDA system 580 comprises: a bottom PLIIM-based unit 586A mounted within the bottom portion of the housing 581; a side PLIIM-based unit 586B mounted within the side portion of the housing 581; an electronic product weigh scale 587, mounted beneath the bottom PLIIM-based unit 587A, in a conventional manner; and a local data communication network 588, mounted within the housing, and establishing a high-speed data communication link between the bottom and side units 586A and 586B, and the electronic weigh scale 587, and a host computer system (e.g. cash register) 589.

As shown in Fig. 33C, the bottom unit 586A comprises: a PLIIM-based PID subsystem 25′ (without LDIP subsystem 122), installed within the bottom portion of the housing 587, for projecting a coplanar PLIB and 1-D FOV through the bottom light transmission aperture 582, on the side closest to the product entry side of the system indicated by the "arrow" (⇐) indicator shown in the figure drawing; a I/O subsystem 127 providing data, address and control buses, and establishing data ports for data input to and data output from the PLIIM-based PID subsystem 25′; and a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588.

As shown in Fig. 33C, the side unit 586B comprises: a PLIIM-based PID subsystem 25′ (with LDIP subsystem 122), installed within the side portion of the housing 581, for projecting (i) a coplanar PLIB and 1-D FOV through the side light transmission aperture 583, also on the side closest to the product entry side of the system indicated by the "arrow" (⇐) indicator shown in the figure drawing, and also (ii) a pair of AM laser beams, angularly spaced from each other, through the side light transmission aperture 583, also on the side closest to the product entry side of the system indicated by the "arrow" (⇐) indicator shown in the figure drawing, but closer to the arrow indicator than the coplanar PLIB and 1-D FOV projected by the

subsystem, thus locating them slightly downstream from the AM laser beams used for product dimensioning and detection; a I/O subsystem 127 for establishing data ports for data input to and data output from the PLIIM-based PIB subsystem 25′; a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588; and a system control computer 590, operably connected to the I/O subsystem 127, for (i) receiving package identification data elements transmitted over the local data communication network by either PLIIM-based PID subsystem 25′, (ii) package dimension data elements transmitted over the local data communication network by the LDIP subsystem 122, and (iii) package weight data elements transmitted over the local data communication network by the electronic weigh scale 587. As shown, LDIP subsystem 122 includes an integrated package/object velocity measurement subsystem

In order that the bioptical PLIIM-based PIDA system 580 is capable of capturing and analyzing color images, and thus enabling, in supermarket environments, "produce recognition" on the basis of color as well as dimensions and geometrical form, each PLIIM-based subsystem 25′ employs (i) a plurality of visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB) from the side and bottom light transmission apertures 582 and 583, and also (ii) a 1-D (linear-type) CCD image detection array for capturing color images of objects (e.g. produce) as the objects are manually transported past the imaging windows 584 and 585 of the bioptical system, along the direction of the indicator arrow, by the user or operator of the system (e.g. retail sales clerk).

Any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the bioptical system 580 to provide an ultra-compact system capable of high performance image acquisition and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using solid-state VLD devices, as taught herein.

Notably, the image processing computer 21 within each PLIIM-based subsystem 25′ is provided with robust image processing software 582 that is designed to process color images captured by the subsystem and determine the shape/geometry, dimensions and color of scanned products in diverse retail shopping environments. In the illustrative embodiment, the IFD subsystem (i.e. "camera") 3″ within the PLIIM-based subsystem 25″ is capable of: (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package

label are transmitted to either an image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations. Such functions are carried out in substantially the same manner as taught in connection with the tunnel-based system shown in Figs. 27 through 32B.

In most POS retail environments, the sales clerk may pass either a UPC or UPC/EAN labeled product past the bioptical system, or an item of produce (e.g. vegetables, fruits, etc.). In the case of UPC labeled products, the image processing computer 21 will decode process images captured by the IFD subsystem 3′ (in conjunction with performing OCR processing for reading trademarks, brandnames, and other textual indicia) as the product is manually moved past the imaging windows of the system in the direction of the arrow indicator. For each product identified by the system, a product identification data element will be automatically generated and transmitted over the data communication network to the system control/management computer 590, for transmission to the host computer (e.g. cash register computer) 589 and use in check-out computations. Any dimension data captured by the LDIP subsystem 122 while identifying a UPC or UPC/EAN labeled product, can be disregarded in most instances; although, in some instances, it might make good sense that such information is automatically transmitted to the system control/management computer 590, for comparison with information in a product information database so as to cross-check that the identified product is in fact the same product indicated by the bar code symbol read by the image processing computer 21. This feature of the bioptical system can be used to increase the accurately of product identification, thereby lowering scan error rates and improving consumer confidence in POS technology.

In the case of an item of produce swept past the light transmission windows of the bioptical system, the image processing computer 21 will automatically process images captured by the IFD subsystem 3″ (using the robust produce identification software mentioned above), alone or in combination with produce dimension data collected by the LDIP subsystem 122. In the preferred embodiment, produce dimension data (generated by the LDIP subsystem 122) will be used in conjunction with produce identification data (generated by the image processing computer 21), in order to enable more reliable identification of produce items, prior to weigh in on the electronic weigh scale 587, mounted beneath the bottom imaging window 584. Thus, the image processing computer 21 within the side unit 586B (embodying the LDIP subsystem 122) can be designated as providing primary color images for produce recognition, and cross-correlation with produce dimension data generated by the LDIP subsystem 122. The image processing computer 21 within the bottom unit (without an LDIP subsystem) can be designated as providing secondary color images for produce recognition, independent of the analysis carried out within the side unit, and produce identification data generated by the bottom unit can be transmitted to the system control/management computer 590, for cross-correlation with

produce identification and dimension data generated by the side unit containing the LDIP subsystem 122.

In alternative embodiments of the bioptical system described above, both the side and bottom units can be provided with an LDIP subsystem 122 for product/produce dimensioning operations. Also, it may be desirable to use a simpler set of image forming optics than that provided within IFD subsystem 3''. Also, it may desirable to use PLIIM-based subsystems which have FOVs that are automatically swept across a large 3-D scanning volume definable between the bottom and side imaging windows 584 and 585. The advantage of this type of system design is that the product or item of produce can be presented to the bioptical system without the need to move the product or produce item past the bioptical system along a predetermined scanning/imaging direction, as required in the illustrative system of Figs. 33A through 33C. With this modification in mind, reference is now made to Figs. 34A through 34C in which an alternative bioptical vision-based product/produce identification system 600 is disclosed employing the PLIIM-based camera system disclosed in Figs. 6D1 through 6E3.

<u>Bioptical PLIIM-Based Product Identification, Dimensioning and Analysis System Of The Second Illustrative Embodiment Of The Present Invention</u>

As shown in Figs. 34A through 34C, a pair of PLIIM-based package identification (PID) systems 25'' of Figs. 6D1 through 6E3 are modified and arranged within a compact POS housing 601 having bottom and side light transmission windows 602 and 603 (beneath bottom and side imaging windows 604 and 605, respectively), to produce a bioptical PLIIM-based product identification, dimensioning and analysis (PIDA) system 600 according to a second illustrative embodiment of the present invention. As shown in Fig. 34C, the bioptical PIDA system 600 comprises: a bottom PLIIM-based unit 606A mounted within the bottom portion of the housing 601; a side PLIIM-based unit 606B mounted within the side portion of the housing 601; an electronic product weigh scale 589, mounted beneath the bottom PLIIM-based unit 606A, in a conventional manner; and a local data communication network 588, mounted within the housing, and establishing a high-speed data communication link between the bottom and side units 606A and 606B, and the electronic weigh scale 589.

As shown in Fig. 34C, the bottom unit 606A comprises: a PLIIM-based PIB subsystem 25'' (without LDIP subsystem 122), installed within the bottom portion of the housing 601, for projecting an automatically swept PLIB and a stationary 3-D FOV through the bottom light transmission window 602; a I/O subsystem 127 providing data, address and control buses, and establishing data ports for data input to and data output from the PLIIM-based PID subsystem

25″; and a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588.

As shown in Fig. 34C, the side unit 606A comprises: a PLIIM-based PID subsystem 25″ (with modified LDIP subsystem 122′), installed within the side portion of the housing 601, for projecting (i) an automatically swept PLIB and a stationary 3-D FOV through the bottom light transmission window 605, and also (ii) a pair of automatically swept AM laser beams 607A, 607B, angularly spaced from each other, through the side light transmission window 604; a I/O subsystem 127 for establishing data ports for data input to and data output from the PLIIM-based PID subsystem 25″; a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588; and a system control data management computer 609, operably connected to the I/O subsystem 127, for (i) receiving package identification data elements transmitted over the local data communication network by either PLIIM-based PID subsystem 25″, (ii) package dimension data elements transmitted over the local data communication network by the LDIP subsystem 122, and (iii) package weight data elements transmitted over the local data communication network by the electronic weigh scale 587. As shown, modified LDIP subsystem 122′ is similar in nearly all respects to LDIP subsystem 122, except that its beam folding mirror 163 is automatically oscillated during dimensioning in order to swept the pair of AM laser beams across the entire 3-D FOV of the side unit of the system when the product or produce item is positioned at rest upon the bottom imaging window 604. In the illustrative embodiment, the PLIIM-based camera subsystem 25″ is programmed to automatically capture images of its 3-D FOV to determine whether or not there is a stationary object positioned on the bottom imaging window 604 for dimensioning. When such an object is detected by this PLIIM-based subsystem, it either directly or indirectly automatically activates LDIP subsystem 122′ to commence laser scanning operations within the 3-D FOV of the side unit and dimension the product or item of produce.

In order that the bioptical PLIIM-based PIDA system 600 is capable of capturing and analyzing color images, and thus enabling, in supermarket environments, "produce recognition" on the basis of color as well as dimensions and geometrical form, each PLIIM-based subsystem 25″ employs (i) a plurality of visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB) from the bottom and side imaging windows 604 and 605, and also (ii) a 2-D (area-type) CCD image detection array for capturing color images of objects (e.g. produce) as the objects are presented to the imaging windows of the bioptical system by the user or operator of the system (e.g. retail sales clerk).

Any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the bioptical system 600 to provide an ultra-compact system capable of high performance image acquisition and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using solid-state VLD devices, as taught herein.

Notably, the image processing computer 21 within each PLIIM-based subsystem 25″ is provided with robust image processing software 610 that is designed to process color images captured by the subsystem and determine the shape/geometry, dimensions and color of scanned products in diverse retail shopping environments. In the illustrative embodiment, the IFD subsystem (i.e. "camera") 3″ within the PLIIM-based subsystem 25″ is capable of: (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (dpi) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either an image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations. Such functions are carried out in substantially the same manner as taught in connection with the tunnel-based system shown in Figs. 27 through 32B.

In most POS retail environments, the sales clerk may pass either a UPC or UPC/EAN labeled product past the bioptical system, or an item of produce (e.g. vegetables, fruits, etc.). In the case of UPC labeled products, the image processing computer 21 will decode process images captured by the IFD subsystem 55″ (in conjunction with performing OCR processing for reading trademarks, brandnames, and other textual indicia) as the product is manually presented to the imaging windows of the system. For each product identified by the system, a product identification data element will be automatically generated and transmitted over the data communication network to the system control/management computer 609, for transmission to the host computer (e.g. cash register computer) 589 and use in check-out computations. Any dimension data captured by the LDIP subsystem 122′ while identifying a UPC or UPC/EAN labeled product, can be disregarded in most instances; although, in some instances, it might make good sense that such information is automatically transmitted to the system control/management computer 609, for comparison with information in a product information database so as to cross-check that the identified product is in fact the same product indicated by the bar code symbol read by the image processing computer 21. This feature of the

bioptical system can be used to increase the accurately of product identification, thereby lowering scan error rates and improving consumer confidence in POS technology.

In the case of an item of produce presented to the imaging windows of the bioptical system, the image processing computer 21 will automatically process images captured by the IFD subsystem 55″ (using the robust produce identification software mentioned above), alone or in combination with produce dimension data collected by the LDIP subsystem 122. In the preferred embodiment, produce dimension data (generated by the LDIP subsystem 122) will be used in conjunction with produce identification data (generated by the image processing computer 21), in order to enable more reliable identification of produce items, prior to weigh in on the electronic weigh scale 587, mounted beneath the bottom imaging window 604. Thus, the image processing computer 21 within the side unit 606B (embodying the LDIP subsystem′) can be designated as providing primary color images for produce recognition, and cross-correlation with produce dimension data generated by the LDIP subsystem 122′. The image processing computer 21 within the bottom unit 606A (without LDIP subsystem 122′) can be designated as providing secondary color images for produce recognition, independent of the analysis carried out within the side unit 606B, and produce identification data generated by the bottom unit can be transmitted to the system control/management computer 609, for cross-correlation with produce identification and dimension data generated by the side unit containing the LDIP subsystem 122′.

In alternative embodiments of the bioptical system described above, it may be desirable to use a simpler set of image forming optics than that provided within IFD subsystem 55″.

<u>PLIIM-Based Systems Employing Planar Laser Illumination Arrays (PLIAs) With Visible Laser Diodes Having Characteristic Wavelengths Residing Within Different Portions Of The Visible Band</u>

Numerous illustrative embodiments of PLIIM-based imaging systems according to the principles of the present invention have been described in detail below. While the illustrative embodiments described above have made reference to the use of multiple VLDs to construct each PLIA, and that the characteristic wavelength of each such VLD is substantially similar, the present invention contemplates providing a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) 6A, 6B comprising a plurality of visible laser diodes having a plurality of different characteristic wavelengths residing within different portions of the visible band. The present invention also contemplates providing such a novel PLIIM-based system, wherein the visible laser diodes within the PLIA thereof are spatially arranged so that the spectral components of each neighboring visible laser diode (VLD) spatially overlap and each portion of the composite planar laser illumination

beam (PLIB) along its planar extent contains a spectrum of different characteristic wavelengths, thereby imparting multi-color illumination characteristics to the composite laser illumination beam. The multi-color illumination characteristics of the composite planar laser illumination beam will reduce the temporal coherence of the laser illumination sources in the PLIA, thereby reducing the speckle noise pattern produced at the image detection array of the PLIIM.

The present invention also contemplates providing a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) comprising a plurality of visible laser diodes (VLDs) which intrinsically exhibit high "spectral mode hopping" spectral characteristics which cooperate on the time domain to reduce the temporal coherence of the laser illumination sources operating in the PLIA, and thereby reduce the speckle noise pattern produced at the image detection array in the PLIIM.

The present invention also contemplates providing a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) 6A, 6B comprising a plurality of visible laser diodes (VLDs) which are "thermally-driven" to exhibit high "mode-hopping" spectral characteristics which cooperate on the time domain to reduce the temporal coherence of the laser illumination sources operating in the PLIA, and thereby reduce the speckle-noise pattern produced at the image detection array in the PLIIM accordance with the principles of the present invention.

In some instances, it may also be desirable to use VLDs having characteristics outside of the visible band, such as in the ultra-violet (UV) and infra-red (IR) regions. In such cases, PLIIM-based subsystems will be produced capable of illuminating objects with planar laser illumination beams having IR and/or UV energy characteristics. Such systems can prove useful in diverse industrial environments where dimensioning and/or imaging in such regions of the electromagnetic spectrum are required or desired.

Planar Laser Illumination Module (PLIM) Fabricated By Mounting A Micro-Sized Cylindrical Lens Array Upon A Linear Array Of Surface Emitting Lasers (SELs) Formed On A Semiconductor Substrate

Various types of planar laser illumination modules (PLIM) have been described in detail above. In general, each PLIM will employ a plurality of linearly arranged laser sources which collectively produce a composite planar laser illumination beam. In certain applications, such as hand-held imaging applications, it will be desirable to construct the hand-held unit as compact and as lightweight as possible. Also, in most applications, it will be desirable to manufacture the PLIMs as inexpensively as possible.

As shown in Figs. 35A and 35B, the present invention addresses the above design criteria by providing a miniature planar laser illumination module (PLIM) on a semiconductor

chip 620 that can be fabricated by aligning and mounting a micro-sized cylindrical lens array 621 upon a linear array of surface emitting lasers (SELs) 622 formed on a semiconductor substrate 623, encapsulated (i.e. encased) in a semiconductor package 624 provided with electrical pins 625, a light transmission window 626 and emitting laser emission in the direction normal to the substrate. The resulting semiconductor chip 620 is designed for installation in any of the PLIIM-based systems disclosed, taught or suggested by the present disclosure, and can be driven into operation using a low-voltage DC power supply. The laser output from the PLIM semiconductor chip 620 is a planar laser illumination beam (PLIB) composed of numerous (e.g. 100-400 or more) spatially incoherent laser beams emitted from the linear array of SELs 622 in accordance with the principles of the present invention.

Preferably, the power density characteristics of the composite PLIB produced from this semiconductor chip 620 should be substantially uniform across the planar extent thereof, i.e. along the working distance of the optical system in which it is employed. If necessary, during manufacture, an additional diffractive optical element (DOE) array can be aligned upon the linear array of SELs 620 prior to placement and alignment of the cylindrical lens array 621. The function of this additional DOE array would be to spatially filter (i.e. smooth out) laser emissions produced from the SEL array so that the composite PLIB exhibits substantially uniform power density characteristics across the planar extent thereof, as required during most illumination and imaging operations. In alternative embodiments, the optional DOE array and the cylindrical lens array can be designed and manufactured as a unitary optical element adapted for placement and mounting on the SEL array 622. While holographic recording techniques can be used to manufacture such diffractive optical lens arrays, it is understood that refractive optical elements can also be used in practice with equivalent results. Also, while end user requirements will typically specify PLIB power characteristics, currently available SEL array fabrication techniques and technology will determine the realizeability of such design specifications.

In general, there are various ways of realizing the PLIIM-based semiconductor chip of the present invention, wherein surface emitting laser (SEL) diodes produce laser emission in the direction normal to the substrate.

In Fig. 36A, a first illustrative embodiment of the PLIM-based semiconductor chip 620 is shown constructed from a plurality of "45 degree mirror" (SELs) 622'. As shown, each 45 degree mirror SEL 627 of the illustrative embodiment comprises: an n-doped quarter-wave GaAs/AlAs stack 628 functioning as the lower distributed Bragg reflector (DBR); an $In_{0.2}Ga_{0.8}As$/GaAs strained quantum well active region 629 in the center of a one-wave $Ga_{0.5}Al_{0.5}As$ spacer; and a p-doped upper GaAs/AlAs stack 630 (grown on a n+-GaAs substrate), functioning as the top DBR; a 45 degree slanted mirror 631 (etched in the n-doped

layer) for reflecting laser emission output from the active region, in a direction normal to the surface of the substrate. Isolation regions 632 are formed between each SEL 627.

As shown in Fig. 36A, a linear array of 45 degree mirror SELs are formed upon the n-doped substrate, and then a micro-sized cylindrical lens array 621 (e.g. diffractive or refractive lens array) is (i) placed upon the SEL array, (ii) aligned with respect to SEL array so that the cylindrical lens array planarizes the output PLIB, and finally (iii) permanently mounted upon the SEL array to produce the monolithic PLIM device of the present invention. As shown in Figs. 35A and 35B, the resulting assembly is then encapsulated within an IC package 624 having a light transmission window 626 through which the composite PLIB may project outwardly in direction substantially normal to the substrate, as well as connector pins 625 for connection to SEL array drive circuits described hereinabove. Preferably, the light transmission window 626 is provided with a narrowly-tuned band-pass spectral filter, permitting transmission of only the spectral components of the composite PLIB produced from the PLIM semiconductor chip.

In Fig. 36B, a second illustrative embodiment of the PLIM-based semiconductor chip is shown constructed from "grating-coupled" surface emitting laser (SELs) 635. As shown, each grating couple SEL 635 comprises: an n-doped GaAs/AlAs stack 636 functioning as the lower distributed Bragg reflector (DBR); an $In_{0.2}Ga_{0.8}As$/GaAs strained quantum well active region 637 in the center of a $Ga_{0.5}Al_{0.5}As$ spacer; and a p-doped upper GaAs/AlAs stack 638 (grown on a n+-GaAs substrate), functioning as the top DBR; and a 2nd order diffraction grating 639, formed in the p-doped layer, for coupling laser emission output from the active region, through the 2nd order grating, and in a direction normal to the surface of the substrate. Isolation regions 640 are formed between each SEL 635.

As shown in Fig. 36B, a linear array of grating-coupled SELs are formed upon the n-doped substrate, and then a micro-sized cylindrical lens array 621 (e.g. diffractive or refractive lens array) is (i) placed upon the SEL array, (ii) aligned with respect to SEL array so that the cylindrical lens array planarizes the output PLIB, and finally (iii) permanently mounted upon the SEL array to produce the monolithic PLIM device of the present invention. As shown in Figs. 35A and 35B, the resulting assembly is then encapsulated within an IC package having a light transmission window 626 through which the composite PLIB may project outwardly in direction substantially normal to the substrate, as well as connector pins 625 for connection to SEL array drive circuits described hereinabove. Preferably, the light transmission window 626 is provided with a narrowly-tuned band-pass spectral filter, permitting transmission of only the spectral components of the composite PLIB produced from the PLIM semiconductor chip.

In Fig. 36C, a third illustrative embodiment of the PLIIM-based semiconductor chip 620 is shown constructed from "vertical cavity" (SELs), or VCSELs. As shown, each VCSEL comprises: an n-doped quarter-wave GaAs/AlAs stack 646 functioning as the lower distributed

Bragg reflector (DBR); an $In_{0.2}Ga_{0.8}As/GaAs$ strained quantum well active region 647 in the center of a one-wave $Ga_{0.5}Al_{0.5}As$ spacer; and a p-doped upper GaAs/AlAs stack 648 (grown on a n+-GaAs substrate), functioning as the top DBR, with the topmost layer is a half-wave-thick GaAs layer to provide phase matching for the metal contact; wherein laser emission from the active region is directed in opposite directions, normal to the surface of the substrate. Isolation regions 649 are provided between each VCSEL 645.

As shown in Fig. 36C, a linear array of VCSELs are formed upon the n-doped substrate, and then a micro-sized cylindrical lens array 621 (e.g. diffractive or refractive lens array) is (i) placed upon the SEL array, (ii) aligned with respect to SEL array so that the cylindrical lens array planarizes the output PLIB, and finally (iii) permanently mounted upon the SEL array to produce the monolithic PLIM device of the present invention. As shown in Figs. 35A and 35B, the resulting assembly is then encapsulated within an IC package having a light transmission window 626 through which the composite PLIB may project outwardly in direction substantially normal to the substrate, as well as connector pins 625 for connection to SEL array drive circuits described hereinabove. Preferably, the light transmission window 626 is provided with a narrowly-tuned band-pass spectral filter, permitting transmission of only the spectral components of the composite PLIB produced from the PLIM semiconductor chip.

Each of the illustrative embodiments of the PLIM-based semiconductor chip described above can be constructed using conventional VCSEL array fabricating techniques well known in the art. Such methods may include, for example, slicing a SEL-type visible laser diode (VLD) wafer into linear VLD strips of numerous (e.g. 200-400) VLDs. Thereafter, a cylindrical lens array 621, made using from light diffractive or refractive optical material, is placed upon and spatially aligned with respect to the top of each VLD strip 622 for permanent mounting, and subsequent packaging within an IC package 624 having an elongated light transmission window 626 and electrical connector pins 625, as shown in Figs. 35A and 35B. For details on such SEL array fabrication techniques, reference can be made to pages 368-413 in the textbook "Laser Diode Arrays" (1994), edited by Dan Botez and Don R. Scifres, and published by Cambridge University Press, under Cambridge Studies in Modern Optics, incorporated herein by reference.

Notably, each SEL in the laser diode array can be designed to emit coherent radiation at a different characteristic wavelengths to produce an array of coplanar laser illumination beams which are substantially temporally and spatially incoherent with respect to each other. This will result in producing from the PLIM-based semiconductor chip, a temporally and spatially coherent-reduced planar laser illumination beam (PLIB), capable of illuminating objects and producing digital images having substantially reduced speckle-noise patterns observable at the

image detection array of the PLIIM-based system in which the PLIM-based semiconductor chip is used (i.e. when used in accordance with the principles of the invention taught herein).

The PLIM semiconductor chip of the present invention can be made to illuminate outside of the visible portion of the electromagnetic spectrum (e.g. over the UV and/or IR portion of the spectrum). Also, the PLIM semiconductor chip of the present invention can be modified to embody laser mode-locking principles, shown in Figs. 1I15C and 1I15D and described in detail above, so that the PLIB transmitted from the chip is temporally-modulated at a sufficient high rate so as to produce ultra-short planes light ensuring substantial levels of speckle-noise pattern reduction during object illumination and imaging applications.

One of the primary advantages of the PLIM-based semiconductor chip of the present invention is that by providing a large number of VCSELs (i.e. real laser sources) on a semiconductor chip beneath a cylindrical lens array, speckle-noise pattern levels can be substantially reduced by an amount proportional to the square root of the number of independent laser sources (real or virtual) employed.

Another advantage of the PLIM-based semiconductor chip of the present invention is that it does not require any mechanical parts or components to produce a spatially and/or temporally coherence-reduced PLIB during system operation.

Also, during manufacture of the PLIM-based semiconductor chip of the present invention, the cylindrical lens array and the VCSEL array can be accurately aligned using substantially the same techniques applied in state-of-the-art photo-lithographic IC manufacturing processes. Also, de-smiling of the output PLIB can be easily corrected during manufacture by simply rotating the cylindrical lens array in front of the VLD strip.

Notably, one or more PLIM-based semiconductor chips of the present invention can be employed in any of the PLIIM-based systems disclosed, taught or suggested herein. Also, it is expected that the PLIM-based semiconductor chip of the present invention will find utility in diverse types of instruments and devices, and diverse fields of technical application.

<u>Fabricating A Planar Laser Illumination And Imaging Module (PLIIM) By Mounting A Pair Of Micro-Sized Cylindrical Lens Arrays Upon A Pair Of Linear Arrays Of Surface Emitting Lasers (SELs) Formed Between A Linear CCD Image Detection Array On A Common Semiconductor Substrate</u>

As shown in Fig. 37, the present invention further contemplates providing a novel planar laser illumination and imaging module (PLIIM) 650 realized on a semiconductor chip. As shown in Fig. 36, a pair of micro-sized (diffractive or refractive) cylindrical lens arrays 651A and 651B are mounted upon a pair of large linear arrays of surface emitting lasers (SELs) 652A and 652B fabricated on opposite sides of a linear CCD image detection array 653. Preferably,

both the linear CCD image detection array 653 and linear SEL arrays 652A and 652B are formed a common semiconductor substrate 654, and encased within an integrated circuit package 655 having electrical connector pins 656, a first and second elongated light transmission windows 657A and 657B disposed over the SEL arrays 652A and 652B, respectively, and a third light transmission window 658 disposed over the linear CCD image detection array 653. Notably, SEL arrays 652A and 652B and linear CCD image detection array 653 must be arranged in optical isolation of each other to avoid light leaking onto the CCD image detector from within the IC package. When so configured, the PLIIM semiconductor chip 650 of the present invention produces a composite planar laser illumination beam (PLIB) composed of numerous (e.g. 400-700) spatially incoherent laser beams, aligned substantially within the planar field of view (FOV) provided by the linear CCD image detection array, in accordance with the principles of the present invention. This PLIIM-based semiconductor chip is powered by a low voltage/low power P.C. supply and can be used in any of the PLIIM-based systems and devices described above. In particular, this PLIIM-based semiconductor chip can be mounted on a mechanically oscillating scanning element in order to sweep both the FOV and coplanar PLIB through a 3-D volume of space in which objects bearing bar code and other machine-readable indicia may pass. This imaging arrangement can be adapted for use in diverse application environments.

<u>Planar Laser Illumination And Imaging Module (PLIIM) Fabricated By Forming A 2D Array Of Surface Emitting Lasers (SELs) About A 2D Area-Type CCD Image Detection Array On A Common Semiconductor Substrate, With A Field of View Defining Lens Element Mounted Over The 2D CCD Image Detection Array and A 2D Array of Cylindrical Lens Elements Mounted Over The 2D Array of SELs</u>

A shown in Figs. 38A and 38B, the present invention also contemplates providing a novel 2D PLIIM-based semiconductor chip 360 embodying a plurality of linear SEL arrays 361A, 361B..., 361n, which are electronically-activated to electro-optically scan (i.e. illuminate) the entire 3-D FOV of a CCD image detection array 362 without using mechanical scanning mechanisms. As shown in Fig. 38B, the miniature 2D VLD/CCD camera 360 of the illustrative embodiment can be realized by fabricating a 2-D array of SEL diodes 361 about a centrally located 2-D area-type CCD image detection array 362, both on a semiconductor substrate 363 and encapsulated within a IC package 364 having connection pins 364, a centrally-located light transmission window 365 positioned over the CCD image detection array 362, and a peripheral light transmission window 366 positioned over the surrounding 2-D array of SEL diodes 361. As shown in Fig. 38B, a light focusing lens element 367 is aligned with and mounted beneath the centrally-located light transmission window 365 to define a 3D field of view (FOV) for

forming images on the 2-D image detection array 362, whereas a 2-D array of cylindrical lens elements 368 is aligned with and mounted beneath the peripheral light transmission window 366 to substantially planarize the laser emission from the linear SEL arrays (comprising the 2-D SEL array 361) during operation. In the illustrative embodiment, each cylindrical lens element 368 is spatially aligned with a row (or column) in the 2-D SEL array 361. Each linear array of SELs 361n in the 2-D SEL array 361, over which a cylindrical lens element 366n is mounted, is electrically addressable (i.e. activatable) by laser diode control and drive circuits 369 which can be fabricated on the same semiconductor substrate. This way, as each linear SEL array is activated, a PLIB 370 is produced therefrom which is coplanar with a cross-sectional portion of the 3-D FOV 371 of the 2-D CCD image detection array. To ensure that laser light produced from the SEL array does not leak onto the CCD image detection array 362, a light buffering (isolation) structure 372 is mounted about the CCD array 362, and optically isolates the CCD array 362 from the SEL array 361 from within the IC package 364 of the PLIIM-based chip 360.

The novel optical arrangement shown in Figs. 3A and 3B enables the illumination of an object residing within the 3D FOV during illumination operations, and formation of an image strip on the corresponding rows (or columns) of detector elements in the CCD array. Notably, beneath each cylindrical lens element 366n (within the 2-D cylindrical lens array 366), there can be provided another optical surface (structure) which functions to widen slightly the geometrical characteristics of the generated PLIB, thereby causing the laser beams constituting the PLIB to diverge slightly as the PLIB travels away from the chip package, ensuring that all regions of the 3D FOV 371 are illuminated with laser illumination, understandably at the expense of a decrease beam power density. Preferably, in this particular embodiment of the present invention, the 2-D cylindrical lens array 366 and FOV-defining optical focusing element 367 are fabricated on the same (plastic) substrate, and designed to produce laser illumination beams having geometrical and optical characteristics that provide optimum illumination coverage while satisfying illumination power requirements to ensuring that the signal-to-noise (SNR) at the CCD image detector 362 is sufficient for the application at hand.

One of the primary advantages of the PLIIM-based semiconductor chip design 360 shown in Figs. 38A and 38B is that its linear SEL arrays 361n can be electronically-activated in order to electro-optically illuminate (i.e. scan) the entire 3-D FOV 371 of the CCD image detection array 362 without using mechanical scanning mechanisms. In addition to the providing a miniature 2D CCD camera with an integrated laser-based illumination system, this novel semiconductor chip 360 also has ultra-low power requirements and packaging constraints enabling its embodiment within diverse types of objects such, as for example, appliances, keychains, pens, wallets, watches, keyboards, portable bar code scanners, stationary bar code scanners, OCR devices, industrial machinery, medical instrumentation, office equipment,

hospital equipment, robotic machinery, retail-based systems, and the like. Applications for PLIIM-based semiconductor chip 360 will only be limited by ones imagination. The SELs in the device may be provided with multi-wavelength characteristics, as well as tuned to operate outside the visible region of the electromagnetic spectrum (e.g. within the IR and UV bands). Also, the present invention contemplates embodying any of the speckle-noise pattern reduction techniques disclosed herein to enable its use in demanding applications where speckle-noise is intolerable. Preferably, the mode-locking techniques taught herein may be embodied within the PLIIM-based semiconductor chip 360 shown in Figs. 38A and 38B so that it generates and repeated scans temporally coherent-reduced PLIBs over the 3D FOV of its CCD image detection array 362.

<u>First Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I1A Through 1I3A</u>

In Fig. 39A, there is shown a first illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention 1200. As shown, the PLIIM-based imager 1200 comprises: a hand-supportable housing 1201; a PLIIM-based image capture and processing engine 1202 contained therein, for projecting a planar laser illumination beam (PLIB) 1203 through its imaging window 1204 in coplanar relationship with the field of view (FOV) 1205 of the linear image detection array 1206 employed in the engine; a LCD display panel 1207 mounted on the upper top surface 1208 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1209 mounted on the middle top surface of the housing 1210 for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1211 contained within the handle of the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1212 with a digital communication network 1213, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 39B, the PLIIM-based image capture and processing engine 1202 comprises: an optical-bench/multi-layer PC board 1214 contained between the upper and lower portions of the engine housing 1215A and 1215B; an IFD (i.e. camera) subsystem 1216 mounted on the optical bench, and including 1-D (i.e. linear) CCD image detection array 1207 having

vertically-elongated image detection elements 1216 and being contained within a light-box 1217 provided with image formation optics 1218, through which laser light collected from the illuminated object along the field of view (FOV) 1205 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 1219A and 1219B mounted on optical bench 1214 on opposite sides of the IFD module 1216, for producing the PLIB 1203 within the FOV 1205; and an optical assembly 1220 including a pair of micro-oscillating cylindrical lens arrays 1221A and 1221B, configured with PLIMs 1219A and 1219B, and a stationary cylindrical lens array 1222, to produce a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I1A through 1I3A. As shown in Fig. 39E, the field of view of the IFD module 1216 spatially-overlaps and is coextensive (i.e. coplanar) with the PLIBs 1203 that are generated by the PLIMs 1219A and 1219B employed therein.

In this illustrative embodiment, cylindrical lens array 1222 is stationary relative to reciprocating cylindrical lens array 1221A, 1221B and the spatial periodicity of the lenslets is higher than the spatial periodicity of lenslets therein in cylindrical lens arrays 1221A, 1221B. In the illustrative embodiment, the physical spacing of cylindrical lens array 1221A, 1221B from its PLIM, and the spacing between cylindrical lens arrays 1221A and 1222 at each PLIM is on the order of about a few millimeters. In the illustrative embodiment, the focal length of each lenslet in the reciprocating cylindrical lens array 1221A, 1221B is about 0.085 inches, whereas the focal length of each lenslet in the stationary cylindrical lens array 1222 is about 0.010 inches. In the illustrative embodiment, the width-to-height dimensions of reciprocating cylindrical lens array is about 7x7 millimeters, whereas the width-to-height dimensions of each reciprocating cylindrical lens array is about 10x10 millimeters. In the illustrative embodiment, the rate of reciprocation of each cylindrical lens array relative to its stationary cylindrical lens array is about 67.0 Hz, with a maximum array displacement of about +/- 0.085 millimeters. It is understood that in alternative embodiments of the present invention, such parameters will naturally vary in order to achieve the level of despeckling performance required by the application at hand.

System Control Architectures For PLIIM-Based Hand-Supportable Linear Imagers Of The Present Invention Employing Linear-Type Image Formation And Detection (IFD) Modules Having A Linear Image Detection Array With Vertically-Elongated Image Detection Elements

In general, there are a various types of system control architectures (i.e. schemes) that can be used in conjunction with any of the hand-supportable PLIIM-based linear-type imagers shown in Figs. 39A through 39C and 41A through 51C, and described throughout the present Specification. Also, there are three principally different types of image forming optics schemes

that can be used to construct each such PLIIM-based linear imager. Thus, it is possible to classify hand-supportable PLIIM-based linear imagers into least fifteen different system design categories based on such criteria. Below, these system design categories will be briefly described with reference to Figs. 40A through 40C5.

<u>System Control Architectures For PLIIM-Based Hand-Supportable Linear Imagers Of The Present Invention Employing Linear-Type Image Formation And Detection (IFD) Modules Having A Linear Image Detection Array With Vertically-Elongated Image Detection Elements And Fixed Focal Length/Fixed Focal Distance Image Formation Optics</u>

In Fig. 40A1, there is shown a manually-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40A1, the PLIIM-based linear imager 1225 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227;a linear-type image formation and detection (IFD) module 1228 having a linear image detection array 1229 with vertically-elongated image detection elements 1230, fixed focal length/fixed focal distance image formation optics 1231, an image frame grabber 1232, and an image data buffer 1233; an image processing computer 1234; a camera control computer 1235; a LCD panel 1236 and a display panel driver 1237; a touch-type or manually-keyed data entry pad 1238 and a keypad driver 1239; and a manually-actuated trigger switch 1240 for manually activating the planar laser illumination arrays, the linear-type image formation and detection (IFD) module, the image frame grabber, the image data buffer, and the image processing computer, via the camera control computer, in response to the manual activation of the trigger switch 1240. Thereafter, the system control program carried out within the camera control computer 1235 enables: (1) the automatic capture of digital images of objects (i.e. bearing bar code symbols and other graphical indicia) through the fixed focal length/fixed focal distance image formation optics 1231 provided within the linear imager; (2) the automatic decode-processing of the bar code symbol represented therein; (3) the automatic generation of symbol character data representative of the decoded bar code symbol; (4) the automatic buffering of the symbol character data within the hand-supportable housing or transmitting the same to a host computer system; and (5) thereafter the automatic deactivation of the subsystem components described above. When using a manually-actuated trigger switch 1240 having a single-stage operation, manually depressing the switch 1240 with a single pull-action will thereafter initiate the above sequence of operations with no further input required by the user.

In an alternative embodiment of the system design shown in Fig. 40A1, manually-actuated trigger switch 1240 would be replaced with a dual-position switch 1240′ having a dual-

positions (or stages of operation) so as to further embody the functionalities of both switch 1240 shown in Fig. 40A1 and transmission activation switch 1261 shown in Fig. 40A2. Also, the system would be further provided with a data transfer mechanism 1260 as shown in Fig. 40A2, for example, so that it embodies the symbol character data transmission functions described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. In such an alternative embodiment, when the user pulls the dual-position switch 1240′ to its first position, the camera control computer 1235 will automatically activate the following components: the planar laser illumination array 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1228, and the image processing computer 1234 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically and repeatedly captured, (2) bar code symbols represented therein are repeatedly decoded, and (3) symbol character data representative of each decoded bar code symbol is automatically generated in a cyclical manner (i.e. after each reading of each instance of the bar code symbol) and buffered in the data transmission mechanism 1260. Then, when the user further depresses the dual-position switch to its second position (i.e. complete depression or activation), the camera control computer 1235 enables the data transmission mechanism 1260 to transmit character data from the imager processing computer 1234 to a host computer system in response to the manual activation of the dual-position switch 1240′ to its second position at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1234 and buffered in data transmission switch 1260. This dual-stage switching mechanism provides the user with an additional degree of control when trying to accurately read a bar code symbol from a bar code menu, on which two or more bar code symbols reside on a single line of a bar code menu, and width of the FOV of the hand-held imager spatially extends over these bar code symbols, making bar code selection challenging if not difficult.

In Fig. 40A2, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40A2, the PLIIM-based linear imager 1245 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1246 having a linear image detection array 1247 with vertically-elongated image detection elements 1248, fixed focal length/fixed focal distance image formation optics 1249, an image frame grabber 1250, and an image data buffer 1251; an image processing computer 1252; a camera control computer 1253; a LCD panel 1254 and a display panel driver 1255; a touch-type or manually-keyed data entry pad 1256 and a keypad

driver 1257; an IR-based object detection subsystem 1258 within its hand-supportable housing for automatically activating, upon detection of an object in its IR-based object detection field 1259, the planar laser illumination arrays 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1246, and the image processing computer 1252, via the camera control computer 1253, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1260 and a manually-activatable data transmission switch 1261, integrated with the hand-supportable housing, for enabling the transmission of symbol character data from the imager processing computer 1252 to a host computer system, via the data transmission mechanism 1260, in response to the manual activation of the data transmission switch 1261 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1252. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In Fig. 40A3, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40A3, the PLIIM-based linear imager 1265 comprises: a planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1266 having a linear image detection array 1267 with vertically-elongated image detection elements 1268, fixed focal length/fixed focal distance image formation optics 1269, an image frame grabber 1270 and an image data buffer 1271; an image processing computer 1272; a camera control computer 1273; a LCD panel 1274 and a display panel driver 1275; a touch-type or manually-keyed data entry pad 1276 and a keypad driver 1277; a laser-based object detection subsystem 1278 embodied within camera control computer for automatically activating the planar laser illumination arrays 6 into a full-power mode of operation, the linear-type image formation and detection (IFD) module 1266, and the image processing computer 1272, via the camera control computer 1273, in response to the automatic detection of an object in its laser-based object detection field 1279, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1280 and a manually-activatable data transmission switch 1281 for

enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1280, in response to the manual activation of the data transmission switch 1281 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1272. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

Notably, in the illustrative embodiment of Fig. 40A3, the PLIIM-based system has an object detection mode, a bar code detection mode, and a bar code reading mode of operation, as taught in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, supra. During the object detection mode of operation of the system, the camera control computer 1293 transmits a control signal to the VLD drive circuitry 11, (optionally via the PLIA microcontroller), causing each PLIM to generate a pulsed-type planar laser illumination beam (PLIB) consisting of planar laser light pulses having a very low duty cycle (e.g. as low as 0.1 %) and **high repetition** frequency (e.g. greater than 1 kHZ), so as to function as a non-visible PLIB-based object sensing beam (and/or bar code detection beam, as the case may be). Then, when the camera control computer receives an activation signal from the laser-based object detection subsystem 1278 (i.e. indicative that an object has been detected by the non-visible PLIB-based object sensing beam), the system automatically advances to either: (i) its bar code detection state, where it increases the power level of the PLIB, collects image data and performs bar code detection operations, and therefrom, to its bar code symbol reading state, in which the output power of the PLIB is further increased, image data is collected and decode processed; or (ii) directly to its bar code symbol reading state, in which the output power of the PLIB is increased, image data is collected and decode processed. A primary advantage of using a pulsed high-frequency/low-duty-cycle PLIB as an object sensing beam is that it consumes minimal power yet enables image capture for automatic object and/or bar code detection purposes, without distracting the user by visibly blinking or flashing light beams which tend to detract from the user's experience. In yet alternative embodiments, however, it may be desirable to drive the VLD in each PLIM so that a visibly blinking PLIB-based object sensing beam (and/or bar code detection beam) is generated during the object detection (and bar code detection) mode of system operation. The visibly blinking PLIB-based object sensing beam will typically consist of planar laser light pulses having a moderate duty cycle (e.g. 25 %) and low repetition frequency (e.g. less than 30HZ). In this alternative embodiment of the present invention, the low frequency blinking nature of the PLIB-based object sensing beam (and/or bar code detection beam) would be rendered visually conspicuous, thereby facilitating

alignment of the PLIB/FOV with the bar code symbol, or graphics being imaged in relatively bright imaging environments.

In Fig. 40A4, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40A4, the PLIIM-based linear imager 1285 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1286 having a linear image detection array 1287 with vertically-elongated image detection elements 1288, fixed focal length/fixed focal distance image formation optics 1289, an image frame grabber 1290 and an image data buffer 1291; an image processing computer 1292; a camera control computer 1293; a LCD panel 1294 and a display panel driver 1295; a touch-type or manually-keyed data entry pad 1296 and a keypad driver 1297; an ambient-light driven object detection subsystem 1298 embodied within the camera control computer 1293, for automatically activating the planar laser illumination arrays 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1286, and the image processing computer 1292, via the camera control computer 1293, upon automatic detection of an object via ambient-light detected by object detection field 1299 enabled by the linear image sensor 1287 within the IFD module 1286, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1300 and a manually-activatable data transmission switch 1301 for enabling the transmission of symbol character data from the imager processing computer 1292 to a host computer system, via the data transmission mechanism 1300, in response to the manual activation of the data transmission switch 1301 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1292. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. Notably, in some applications, the passive-mode objection detection subsystem 1298 employed in this system might require (i) using a different system of optics for collecting ambient light from objects during the object detection mode of the system, or (ii) modifying the light collection characteristics of the light collection system to permit increased levels of ambient light to be focused onto the CCD image detection array 1287 in the IFD module (i.e. subsystem). In other applications, the provision of image intensification optics on the surface of the CCD image

detection array should be sufficient to form images of sufficient brightness to perform object detection and/or bar code detection operations.

In Fig. 40A5, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40A5, the PLIIM-based linear imager 1305 comprises: a planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1306 having a linear image detection array 1307 with vertically-elongated image detection elements 1308, fixed focal length/fixed focal distance image formation optics 1309, an image frame grabber 1310, and image data buffer 1311; an image processing computer 1312; a camera control computer 1313; a LCD panel 1314 and a display panel driver 1315; a touch-type or manually-keyed data entry pad 1316 and a keypad driver 1317; an automatic bar code symbol detection subsystem 1318 embodied within camera control computer 1313 for automatically activating the image processing computer for decode-processing in response to the automatic detection of a bar code symbol within its bar code symbol detection field by the linear image sensor within the IFD module 1306 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1319 and a manually-activatable data transmission switch 1320 for enabling the transmission of symbol character data from the imager processing computer 1312 to a host computer system, via the data transmission mechanism 1319, in response to the manual activation of the data transmission switch 1320 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

<u>System Control Architectures For PLIIM-Based Hand-Supportable Linear Imagers Of The Present Invention Employing Linear-Type Image Formation And Detection (IFD) Modules Having A Linear Image Detection Array With Vertically-Elongated Image Detection Elements And Fixed Focal Length/Variable Focal Distance Image Formation Optics</u>

In Fig. 40B1, there is shown a manually-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40B1, the PLIIM-based linear imager 1325 comprises: a planar laser illumination array

(PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1326 having a linear image detection array 1328 with vertically-elongated image detection elements 1329, fixed focal length/variable focal distance image formation optics 1330, an image frame grabber 1331, and an image data buffer 1332; an image processing computer 1333; a camera control computer 1334; a LCD panel 1335 and a display panel driver 1336; a touch-type or manually-keyed data entry pad 1337 and a keypad driver 1338; and a manually-actuated trigger switch 1339 for manually activating the planar laser illumination arrays 6, the linear-type image formation and detection (IFD) module 1326, and the image processing computer 1333, via the camera control computer 1334, in response to manual activation of the trigger switch 1339. Thereafter, the system control program carried out within the camera control computer 1334 enables: (1) the automatic capture of digital images of objects (i.e. bearing bar code symbols and other graphical indicia) through the fixed focal length/fixed focal distance image formation optics 1330 provided within the linear imager; (2) decode–processing the bar code symbol represented therein; (3) generating symbol character data representive of the decoded bar code symbol; (4) buffering the symbol character data within the hand-supportable housing or transmitting the same to a host computer system; and (5) thereafter automatically deactivating the subsystem components described above. When using a manually-actuated trigger switch 1339 having a single-stage operation, manually depressing the switch 1339 with a single pull-action will thereafter initiate the above sequence of operations with no further input required by the user.

In an alternative embodiment of the system design shown in Fig. 40B1, manually-actuated trigger switch 1339 would be replaced with a dual-position switch 1339′ having a dual-positions (or stages of operation) so as to further embody the functionalities of both switch 1339 shown in Fig. 40B1 and transmission activitation switch 1356 shown in Fig. 40B2. Also, the system would be further provided with a data transfer mechanism 1355 as shown in Fig. 40B2, for example, so that it embodies the symbol character data transmission functions described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. In such an alternative embodiment, when the user pulls the dual-position switch 1339′ to its first position, the camera control computer 1348 will automatically activate the following components: the planar laser illumination array 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1341, and the image processing computer 1347 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically and repeatedly captured, (2) bar code symbols represented therein are repeatedly decoded, and (3) symbol character data representative of each decoded bar code

symbol is automatically generated in a cyclical manner (i.e. after each reading of each instance of the bar code symbol) and buffered in the data transmission mechanism 1335. Then, when the user further depresses the dual-position switch to its second position (i.e. complete depression or activation), the camera control computer 1248 enables the data transmission mechanism 1355 to transmit character data from the imager processing computer 1347 to a host computer system in response to the manual activation of the dual-position switch 1339′ to its second position at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1347 and buffered in data transmission mechanism 1355 This dual-stage switching mechanism provides the user with an additional degree of control when trying to accurately read a bar code symbol from a bar code menu, on which two or more bar code symbols reside on a single line of a bar code menu, and width of the FOV of the hand-held imager spatially extends over these bar code symbols, making bar code selection challenging if not difficult.

In Fig. 40B2, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40B2, the PLIIM-based linear imager 1340 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1341 having a linear image detection array 1342 with vertically-elongated image detection elements 1343, fixed focal length/variable focal distance image formation optics 1344, an image frame grabber 1345, and an image data buffer 1346; an image processing computer 1347; a camera control computer 1348; a LCD panel 1349 and a display panel driver 1350; a touch-type or manually-keyed data entry pad 1351 and a keypad driver 1352; an IR-based object detection subsystem 1353 within its hand-supportable housing for automatically activating upon detection of an object in its IR-based object detection field 1354, the planar laser illumination arrays 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1341, as well as the image processing computer 1347, via the camera control computer 1348, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1355 and a manually-activatable data transmission switch 1356 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1355, in response to the manual activation of the data transmission switch 1356 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated from the image

processing computer 1347. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In Fig. 40B3, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40B3, the PLIIM-based linear imager 1361 comprises: a planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1361 having a linear image detection array 1362 with vertically-elongated image detection elements 1363, fixed focal length/variable focal distance image formation optics 1364, an image frame grabber 1365, and an image data buffer 1366; an image processing computer 1367; a camera control computer 1368; a LCD panel 1369 and a display panel driver 1370; a touch-type or manually-keyed data entry pad 1371 and a keypad driver 1372; a laser-based object detection subsystem 1373 embodied within the camera control computer 1368 for automatically activating the planar laser illumination arrays 6 into a full-power mode of operation, the linear-type image formation and detection (IFD) module 1366, and the image processing computer 1367, via the camera control computer 1373, in response to the automatic detection of an object in its laser-based object detection field 1374, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1375 and a manually-activatable data transmission switch 1376 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1375 in response to the manual activation of the data transmission switch 1376 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1367. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In the illustrative embodiment of Fig. 40B3, the PLIIM-based system has an object detection mode, a bar code detection mode, and a bar code reading mode of operation, as taught in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, supra. During the object detection mode of operation of the system, the camera control computer 1368 transmits a control signal to the VLD drive circuitry 11,

(optionally via the PLIA microcontroller), causing each PLIM to generate a pulsed-type planar laser illumination beam (PLIB) consisting of planar laser light pulses having a very low duty cycle (e.g. as low as 0.1 %) and high repetition frequency (e.g. greater than 1 kHZ), so as to function as a non-visible PLIB-based object sensing beam (and/or bar code detection beam, as the case may be). Then, when the camera control computer receives an activation signal from the laser-based object detection subsystem 1373 (i.e. indicative that an object has been detected by the non-visible PLIB-based object sensing beam), the system automatically advances to either: (i) its bar code detection state, where it increases the power level of the PLIB, collects image data and performs bar code detection operations, and therefrom, to its bar code symbol reading state, in which the output power of the PLIB is further increased, image data is collected and decode processed; or (ii) directly to its bar code symbol reading state, in which the output power of the PLIB is increased, image data is collected and decode processed. A primary advantage of using a pulsed high-frequency/low-duty-cycle PLIB as an object sensing beam is that it consumes minimal power yet enables image capture for automatic object and/or bar code detection purposes, without distracting the user by visibly blinking or flashing light beams which tend to detract from the user's experience. In yet alternative embodiments, however, it may be desirable to drive the VLD in each PLIM so that a visibly blinking PLIB-based object sensing beam (and/or bar code detection beam) is generated during the object detection (and bar code detection) mode of system operation. The visibly blinking PLIB-based object sensing beam will typically consist of planar laser light pulses having a moderate duty cycle (e.g. 25 %) and low repetition frequency (e.g. less than 30HZ). In this alternative embodiment of the present invention, the low frequency blinking nature of the PLIB-based object sensing beam (and/or bar code detection beam) would be rendered visually conspicuous, thereby facilitating alignment of the PLIB/FOV with the bar code symbol, or graphics being imaged in relatively bright imaging environments.

In Fig. 40B4, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40B4, the PLIIM-based linear imager 1380 comprises: a planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1381 having a linear image detection array 1382 with vertically-elongated image detection elements 1383, fixed focal length/variable focal distance image formation optics 1384, an image frame grabber 1385, and an image data buffer 1386; an image processing computer 1387; a camera control computer 1388; a LCD panel 1389 and a display panel driver 1390; a touch-type or manually-keyed data entry pad 1391 and a keypad driver 1392; an ambient-light driven object detection subsystem 1393 embodied within the

camera control computer 1388 for automatically activating the planar laser illumination arrays 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1386, and the image processing computer 1387, via the camera control computer 1388, in response to the automatic detection of an object via ambient-light detected by object detection field 1394 enabled by the linear image sensor within the IFD module 1381, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1395 and a manually-activatable data transmission switch 1396 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1395 in response to the manual activation of the data transmission switch 1395 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1387. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. Notably, in some applications, the passive-mode objection detection subsystem 1393 employed in this system might require (i) using a different system of optics for collecting ambient light from objects during the object detection mode of the system, or (ii) modifying the light collection characteristics of the light collection system to permit increased levels of ambient light to be focused onto the CCD image detection array 1382 in the IFD module (i.e. subsystem). In other applications, the provision of image intensification optics on the surface of the CCD image detection array should be sufficient to form images of sufficient brightness to perform object detection and/or bar code detection operations.

In Fig. 40B5, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40B5, the PLIIM-based linear imager 1400 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1401 having a linear image detection array 1402 with vertically-elongated image detection elements 1403, fixed focal length/variable focal distance image formation optics 14054, an image frame grabber 1405, and an image data buffer 1406; an image processing computer 1407; a camera control computer 1409, a LCD panel 1409 and a display panel driver 1410; a touch-type or manually-keyed data entry pad 1411 and a keypad driver 1412; an automatic bar code symbol detection subsystem 1413 embodied within camera

control computer 1408 for automatically activating the image processing computer for decode-processing upon automatic detection of a bar code symbol within its bar code symbol detection field by the linear image sensor within the IFD module 1401 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1414 and a manually-activatable data transmission switch 1415 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1414, in response to the manual activation of the data transmission switch 1415 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1407. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

System Control Architectures For PLIIM-Based Hand-Supportable Linear Imagers Of The Present Invention Employing Linear-Type Image Formation And Detection (IFD) Modules Having A Linear Image Detection Array With Vertically-Elongated Image Detection Elements And Variable Focal Length/Variable Focal Distance Image Formation Optics

In Fig. 40C1, there is shown a manually-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40C1, the PLIIM-based linear imager 1420 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1421 having a linear image detection array 1422 with vertically-elongated image detection elements 1423, variable focal length/variable focal distance image formation optics 1424, an image frame grabber 1425, and an image data buffer 1426; an image processing computer 1427; a camera control computer 1428; a LCD panel 1429 and a display panel driver 1430; a touch-type or manually-keyed data entry pad 1431 and a keypad driver 1432; and a manually-actuated trigger switch 1433 for manually activating the planar laser illumination array 6, the linear-type image formation and detection (IFD) module 1421, and the image processing computer 1427, via the camera control computer 1428, in response to the manual activation of the trigger switch 1433. Thereafter, the system control program carried out within the camera control computer 1428 enables: (1) the automatic capture of digital images of objects (i.e. bearing bar code symbols and other graphical indicia) through the fixed

focal length/fixed focal distance image formation optics 1424 provided within the linear imager; (2) decode–processing the bar code symbol represented therein; (3) generating symbol character data representive of the decoded bar code symbol; (4) buffering the symbol character data within the hand-supportable housing or transmitting the same to a host computer system; and (5) thereafter automatically deactivating the subsystem components described above. When using a manually-actuated trigger switch 1433 having a single-stage operation, manually depressing the switch 1433 with a single pull-action will thereafter initiate the above sequence of operations with no further input required by the user.

In an alternative embodiment of the system design shown in Fig. 40C1, manually-actuated trigger switch 1433 would be replaced with a dual-position switch 1433′ having a dual-positions (or stages of operation) so as to further embody the functionalities of both switch 1433 shown in Fig. 40C1 and transmission activitation switch 1451 shown in Fig. 40C2. Also, the system would be further provided with a data transmission mechanism 1450 as shown in Fig. 40C2, for example, so that it embodies the symbol character data transmission functions described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. In such an alternative embodiment, when the user pulls the dual-position switch 1433′ to its first position, the camera control computer 1428 will automatically activate the following components: the planar laser illumination array 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1421, and the image processing computer 1427 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically and repeatedly captured, (2) bar code symbols represented therein are repeatedly decoded, and (3) symbol character data representative of each decoded bar code symbol is automatically generated in a cyclical manner (i.e. after each reading of each instance of the bar code symbol) and buffered in the data transmission mechanism 1260. Then, when the user further depresses the dual-position switch to its second position (i.e. complete depression or activation), the camera control computer 1428 enables the data transmission mechanism 1401 to transmit character data from the imager processing computer 1427 to a host computer system in response to the manual activation of the dual-position switch 1433′ to its second position at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1427 and buffered in data transmission mechanism 1450. This dual-stage switching mechanism provides the user with an additional degree of control when trying to accurately read a bar code symbol from a bar code menu, on which two or more bar code symbols reside on a single line of a bar code menu, and width of

the FOV of the hand-held imager spatially extends over these bar code symbols, making bar code selection challenging if not difficult.

In Fig. 40C2, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40C2, the PLIIM-based linear imager 1435 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1436 having a linear image detection array 1437 with vertically-elongated image detection elements 1438, variable focal length/variable focal distance image formation optics 1439, an image frame grabber 1440, and an image data buffer 1441; an image processing computer 1442; a camera control computer 1443; a LCD panel 1444 and a display panel driver 1445; a touch-type or manually-keyed data entry pad 1446 and a keypad driver 1447; an IR-based object detection subsystem 1448 within its hand-supportable housing for automatically activating upon detection of an object in its IR-based object detection field 1449, the planar laser illumination arrays 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1436, as well the image processing computer 1442, via the camera control computer 1443, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1450 and a manually-activatable data transmission switch 1451 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1450, in response to the manual activation of the data transmission switch 1451 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1442. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In Fig. 40C3, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40C3, the PLIIM-based linear imager 1455 comprises: a planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1456 having a linear image detection array 1457 with vertically-elongated image detection elements 1458, variable focal length/variable focal distance

image formation optics 1459, an image frame grabber 1460, and an image data buffer 1461; an image processing computer 1462; a camera control computer 1463; a LCD panel 1464 and a display panel driver 1465; a touch-type or manually-keyed data entry pad 1466 and a keypad driver 1467; a laser-based object detection subsystem 1468 within its hand-supportable housing for automatically activating the planar laser illumination array 6 into a full-power mode of operation, the linear-type image formation and detection (IFD) module 1456, and the image processing computer 1462, via the camera control computer 1463, in response to the automatic detection of an object in its laser-based object detection field 1469, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1470 and a manually-activatable data transmission switch 1471 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1470, in response to the manual activation of the data transmission switch 1471 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1462. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In the illustrative embodiment of Fig. 40C3, the PLIIM-based system has an object detection mode, a bar code detection mode, and a bar code reading mode of operation, as taught in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, supra. During the object detection mode of operation of the system, the camera control computer 1463 transmits a control signal to the VLD drive circuitry 11, (optionally via the PLIA microcontroller), causing each PLIM to generate a pulsed-type planar laser illumination beam (PLIB) consisting of planar laser light pulses having a very low duty cycle (e.g. as low as 0.1 %) and high repetition frequency (e.g. greater than 1 kHZ), so as to function as a non-visible (i.e. invisible) PLIB-based object sensing beam (and/or bar code detection beam, as the case may be). Then, when the camera control computer receives an activation signal from the laser-based object detection subsystem 1468 (i.e. indicative that an object has been detected by the non-visible PLIB-based object sensing beam), the system automatically advances to either: (i) its bar code detection state, where it increases the power level of the PLIB, collects image data and performs bar code detection operations, and therefrom, to its bar code symbol reading state, in which the output power of the PLIB is further increased, image data is collected and decode processed; or (ii) directly to its bar code symbol

reading state, in which the output power of the PLIB is increased, image data is collected and decode processed. A primary advantage of using a pulsed high-frequency/low-duty-cycle PLIB as an object sensing beam is that it consumes minimal power yet enables image capture for automatic object and/or bar code detection purposes, without distracting the user by visibly blinking or flashing light beams which tend to detract from the user's experience. In yet alternative embodiments, however, it may be desirable to drive the VLD in each PLIM so that a visibly blinking PLIB-based object sensing beam (and/or bar code detection beam) is generated during the object detection (and bar code detection) mode of system operation. The visibly blinking PLIB-based object sensing beam will typically consist of planar laser light pulses having a moderate duty cycle (e.g. 25 %) and low repetition frequency (e.g. less than 30HZ). In this alternative embodiment of the present invention, the low frequency blinking nature of the PLIB-based object sensing beam (and/or bar code detection beam) would be rendered visually conspicuous, thereby facilitating alignment of the PLIB/FOV with the bar code symbol, or graphics being imaged in relatively bright imaging environments.

In Fig. 40C4, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, or example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40C4, the PLIIM-based linear imager 1475 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1476 having a linear image detection array 1477 with vertically-elongated image detection elements 1478, variable focal length/variable focal distance image formation optics 1479, an image frame grabber 1480, and an image data buffer 1481; an image processing computer 1482; a camera control computer 1483; a LCD panel 1484 and a display panel driver 1485; a touch-type or manually-keyed data entry pad 1486 and a keypad driver 1487; an ambient-light driven object detection subsystem 1488 embodied within the camera control computer 1488, for automatically activating the planar laser illumination arrays 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 1476, and the image processing computer 1482, via the camera control computer 1483, in response to the automatic detection of an object via ambient-light detected by object detection field 1489 enabled by the linear image sensor within the IFD 1476 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1490 and a manually-activatable data transmission switch 1491 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1490, in response to the manual

activation of the data transmission switch 1491 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1482. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. Notably, in some applications, the passive-mode objection detection subsystem 1488 employed in this system might require (i) using a different system of optics for collecting ambient light from objects during the object detection mode of the system, or (ii) modifying the light collection characteristics of the light collection system to permit increased levels of ambient light to be focused onto the CCD image detection array 1477 in the IFD module (i.e. subsystem). In other applications, the provision of image intensification optics on the surface of the CCD image detection array should be sufficient to form images of sufficient brightness to perform object detection and/or bar code detection operations.

In Fig. 40C5, there is shown an automatically-activated version of the PLIIM-based linear imager as illustrated, for example, in Figs. 39A through 39C and 41A through 51C. As shown in Fig. 40C5, the PLIIM-based linear imager 1495 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, and an integrated despeckling mechanism 1226 having a stationary cylindrical lens array 1227; a linear-type image formation and detection (IFD) module 1496 having a linear image detection array 1497 with vertically-elongated image detection element 1498, variable focal length/variable focal distance image formation optics 1499, an image frame grabber 1500, and an image data buffer 1501; an image processing computer 1502; a camera control computer 1503; a LCD panel 1504 and a display panel driver 1505; a touch-type or manually-keyed data entry pad 1506 and a keypad driver 1507; an automatic bar code symbol detection subsystem 1508 embodied within the camera control computer 1508 for automatically activating the image processing computer for decode-processing upon automatic detection of a bar code symbol within its bar code symbol detection field 1509 by the linear image sensor within the IFD module 1496 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1510 and a manually-activatable data transmission switch 1511 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1510, in response to the manual activation of the data transmission switch 1511 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is

automatically generated by the image processing computer 1502. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

Second Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I6A And 1I6B

In Fig. 41A, there is shown a second illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1520 comprises: a hand-supportable housing 1521; a PLIIM-based image capture and processing engine 1522 contained therein, for projecting a planar laser illumination beam (PLIB) 1523 through its imaging window 1524 in coplanar relationship with the field of view (FOV) 1525 of the linear image detection array 1526 employed in the engine; a LCD display panel 1527 mounted on the upper top surface 1528 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1529 mounted on the middle top surface 1530 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1531 contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface with a digital communication network, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 41B, the PLIIM-based image capture and processing engine 1522 comprises: an optical-bench/multi-layer PC board 1532 contained between the upper and lower portions of the engine housing 1534A and 1534B; an IFD module (i.e. camera subsystem) 1535 mounted on the optical bench 1532, and including 1-D CCD image detection array 1536 having vertically-elongated image detection elements 1537 and being contained within a light-box 1538 provided with image formation optics 1539 through which light collected from the illuminated object along a field of view (FOV) 1540 is permitted to pass; a pair of PLIMs (i.e. PLIA) 1541A and 1541B mounted on optical bench 1532 on opposite sides of the IFD module 1535, for producing a PLIB 1542 within the FOV 1540; and an optical assembly 1543 including a pair of Bragg cell structures 1544A and 1544B, and a pair of stationary cylindrical lens arrays 1545A

and 1545B closely configured with PLIMs 1541A and 1541B, respectively, to produce a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I6A through 1I6B. As shown in Fig. 41D, the field of view of the IFD module 1535 spatially-overlaps and is coextensive (i.e. coplanar) with the PLIBs that are generated by the PLIMs 1541A and 1541B employed therein.

In this illustrative embodiment, each cylindrical lens array 1545A (1545B) is stationary relative to its Bragg-cell panel 1544A (1544B). In the illustrative embodiment, the height-to-width dimensions of each Bragg cell structure is about 7x7 millimeters, whereas the width-to-height dimensions of stationary cylindrical lens array is about 10x10 millimeters. It is understood that in alternative embodiments, such parameters will naturally vary in order to achieve the level of despeckling performance required by the application at hand.

<u>Third Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I12G And 1I12H</u>

In Fig. 42A, there is shown a third illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1550 comprises: a hand-supportable housing 1551; a PLIIM-based image capture and processing engine 1552 contained therein, for projecting a planar laser illumination beam (PLIB) 1553 through its imaging window 1554 in coplanar relationship with the field of view (FOV) 1555 of the linear image detection array 1556 employed in the engine; a LCD display panel 1557 mounted on the upper top surface 1558 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1559 mounted on the middle top surface 1560 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1561 contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1562 with a digital communication network 1563, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 42B, the PLIIM-based image capture and processing engine 1552 comprises: an optical-bench/multi-layer PC board 1564 contained between the upper and lower portions of the engine housing 1565A and 1565B; an IFD (i.e. camera) subsystem 1566 mounted

on the optical bench 1564, and including 1-D CCD image detection array 1567 having vertically-elongated image detection elements 1568 and being contained within a light-box 1569 provided with image formation optics 1570, through which light collected from the illuminated object along a field of view (FOV) 1571 is permitted to pass; a pair of PLIMs (i.e. single VLD PLIAs) 1572A and 1572B mounted on optical bench 1564 on opposite sides of the IFD module 1566, for producing a PLIB 1573 within the FOV; and an optical assembly 1575 configured with each PLIM , including a beam folding mirror 1576 mounted before the PLIM, a micro-oscillating mirror 1577 mounted above the PLIM, and a stationary cylindrical lens array 1578 mounted before the micro-oscillating mirror 1577, as shown, to produce a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I6A through 1I6B. As shown in Fig. 41D, the field of view of the IFD module 1566 spatially-overlaps and is coextensive (i.e. coplanar) with the PLIBs that are generated by the PLIMs 1572A and 1572B employed therein.

In this illustrative embodiment, the height to width dimensions of beam folding mirror 1576 is about 10x10 millimeters. The width-to-height dimensions of micro-oscillating mirror **1577 is a about 11x11 and the height to weight dimension of the cylindrical lens array 1578 is** about 12x12 millimeters. It is understood that in alternative embodiments, such parameters will naturally vary in order to achieve the level of despeckling performance required by the application at hand.

Fourth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I7A Through 1I7C

In Fig. 43A, there is shown a fourth illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1580 comprises: a hand-supportable housing 1581; a PLIIM-based image capture and processing engine 1582 contained therein, for projecting a planar laser illumination beam (PLIB) 1583 through its imaging window 1584 in coplanar relationship with the field of view (FOV) 1585 of the linear image detection array 1586 employed in the engine; a LCD display panel 1587 mounted on the upper top surface 1588 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1589 mounted on the middle top surface 1590 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1591, contained

within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1592 with a digital communication network 1593, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 43B, the PLIIM-based image capture and processing engine 1582 comprises: an optical-bench/multi-layer PC board 1594, contained between the upper and lower portions of the engine housing 1595A and 1595B; an IFD (i.e. camera) subsystem 1596 mounted on the optical bench, and including 1-D CCD image detection array 1586 having vertically-elongated image detection elements 1597 and being contained within a light-box 1598 provided with image formation optics 1599, through which light collected from the illuminated object along the field of view (FOV) 1585 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 1600A and 1600B mounted on optical bench 1594 on opposite sides of the IFD module 1596, for producing the PLIB within the FOV; and an optical assembly 1601 configured with each PLIM, including a piezo-electric deformable mirror (DM) 1602 mounted before the PLIM, a beam folding mirror 1603 mounted above the PLIM, and a cylindrical lens array 1604 mounted before the beam folding mirror 1603, to produce a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I7A through 1I7C. As shown in Fig. 43D, the field of view of the IFD module 1596 spatially-overlaps and is coextensive (i.e. coplanar) with the PLIBs that are generated by the PLIMs 1600A and 1600B employed therein.

In this illustrative embodiment, the height to width dimensions of the DM structure 1602 is about 7x7 millimeters. The width-to-height dimensions of stationary cylindrical lens array 1604 is about 10x10 millimeters. It is understood that in alternative embodiments, such parameters will naturally vary in order to achieve the level of despeckling performance required by the application at hand.

<u>Fifth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I8F Through 1I8G</u>

In Fig. 44A, there is shown a fifth illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1610 comprises: a hand-supportable housing 1611; a PLIIM-based image capture and processing engine 1612 contained therein, for projecting a planar laser illumination beam (PLIB) 1613 through its imaging window 1614 in coplanar relationship with the field of view (FOV) 1615 of

the linear image detection array 1616 employed in the engine; a LCD display panel 1617 mounted on the upper top surface 1618 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1619 mounted on the middle top surface 1620 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1621, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1622 with a digital communication network 1623, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 44B, the PLIIM-based image capture and processing engine 1612 comprises: an optical-bench/multi-layer PC board 1624, contained between the upper and lower portions of the engine housing 1625A and 1625B; an IFD (i.e. camera) subsystem 1626 mounted on the optical bench, and including 1-D CCD image detection array 1616 having vertically-elongated image detection elements 1627 and being contained within a light-box 1628 provided with image formation optics 1628, through which light collected from the illuminated object along field of view (FOV) 1613 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 1629A and 1629B mounted on optical bench 1624 on opposite sides of the IFD module, for producing PLIB 1613 within the FOV 1615; and an optical assembly 1630 configured with each PLIM, including a phase-only LCD-based phase modulation panel 1631 and a cylindrical lens array 1632 mounted before the PO-LCD phase modulation panel 1631 to produce a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I8A through 1I8B. As shown in Fig. 44D, the field of view of the IFD module 1626 spatially-overlaps and is coextensive (i.e. coplanar) with the PLIBs that are generated by the PLIMs 1629A and 1629B employed therein.

In this illustrative embodiment, the height to width dimensions of the PO-only LCD-based phase modulation panel 1631 is about 7x7 millimeters. The width-to-height dimensions of stationary cylindrical lens array 1632 is about 9x9 millimeters. It is understood that in alternative embodiments, such parameters will naturally vary in order to achieve the level of despeckling performance required by the application at hand.

Sixth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I12A Through 1I12B

In Fig. 45A, there is shown a sixth illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1635 comprises: a hand-supportable housing 1636; a PLIIM-based image capture and processing engine 1637 contained therein, for projecting a planar laser illumination beam (PLIB) 1638 through its imaging window 1639 in coplanar relationship with the field of view (FOV) 1640 of the linear image detection array 1641 employed in the engine; a LCD display panel 1642 mounted on the upper top surface 1643 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1644 mounted on the middle top surface 1645 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1646, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1647 with a digital communication network 1648, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 45B, the PLIIM-based image capture and processing engine 1642 comprises: an optical-bench/multi-layer PC board 1649, contained between the upper and lower portions of the engine housing 1650A and 1650B; an IFD module (i.e. camera subsystem) 1651 mounted on the optical bench, and including 1-D CCD image detection array 1641 having vertically-elongated image detection elements 1652 and being contained within a light-box 1653 provided with image formation optics 1654, through which light collected from the illuminated object along field of view (FOV) 1640 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 1655A and 1655B mounted on optical bench 1649 on opposite sides of the IFD module, for producing a PLIB within the FOV; and an optical assembly 1656 configured with each PLIM, including a rotating multi-faceted cylindrical lens array structure 1657 mounted before a cylindrical lens array 1658, to produce a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I12A through 1I12B. As shown in Fig. 45D, the field of view of the IFD module spatially-overlaps and is coextensive (i.e. coplanar) with the PLIBs that are generated by the PLIMs 1655A and 1655B employed therein.

<u>Seventh Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Second Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I14A Through 1I14B</u>

In Fig. 46A, there is shown a seventh illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1660 comprises: a hand-supportable housing 1661; a PLIIM-based image capture and processing engine 1662 contained therein, for projecting a planar laser illumination beam (PLIB) 1663 through its imaging window 1664 in coplanar relationship with the field of view (FOV) 1665 of the linear image detection array 1666 employed in the engine; a LCD display panel 1667 mounted on the upper top surface 1668 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1669 mounted on the middle top surface 1670 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1671, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1672 with a digital communication network 1673, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 46B, the PLIIM-based image capture and processing engine 1662 comprises: an optical-bench/multi-layer PC board 1674, contained between the upper and lower portions of the engine housing 1675A and 1675B; an IFD (i.e. camera) subsystem 1676 mounted on the optical bench, and including 1-D CCD image detection array 1666 having vertically-elongated image detection elements 1677 and being contained within a light-box 1678 provided with image formation optics 1679, through which light collected from the illuminated object along field of view (FOV) 1665 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 1680A and 1680B mounted on optical bench 1674 on opposite sides of the IFD module 1676, for producing PLIB 1663 within the FOV 1665; and an optical assembly 1681 configured with each PLIM, including a high-speed temporal intensity modulation panel 1682 mounted before a cylindrical lens array 1683, to produce a despeckling mechanism that operates in accordance with the second generalized method of speckle-pattern noise reduction illustrated in Figs. 1I14A through 1I14B. As shown in Fig. 46D, the field of view of the IFD

module 1678 spatially-overlaps and is coextensive (i.e. coplanar) with the PLIBs that are generated by the PLIMs 1680A and 1680B employed therein.

Notably, the PLIIM-based imager 1660 may be modified to include the use of visible mode locked laser diodes (MLLDs), in lieu of temporal intensity modulation 1682, so to produce a PLIB comprising an optical pulse train with ultra-short optical pulses repeated at a high rate, having numerous high-frequency spectral components which reduce the RMS power of speckle-noise patterns observed at the image detection array of the PLIIM-based system, as described in detail hereinabove.

Eighth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Third Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I17A And 1I17B

In Fig. 47A, there is shown a eighth illustrative embodiment of the PLIIM-based hand-supportable imager 1690 of the present invention. As shown, the PLIIM-based imager 1690 comprises: a hand-supportable housing 1691; a PLIIM-based image capture and processing engine 1692 contained therein, for projecting a planar laser illumination beam (PLIB) 1693 through its imaging window 1694 in coplanar relationship with the field of view (FOV) 1695 of the linear image detection array 1696 employed in the engine; a LCD display panel 1697 mounted on the upper top surface 1698 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1699 mounted on the middle top surface 1700 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1701, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1702 with a digital communication network 1703, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 47B, the PLIIM-based image capture and processing engine 1692 comprises: an optical-bench/multi-layer PC board 1704, contained between the upper and lower portions of the engine housing 1705A and 1705B; an IFD (i.e. camera) subsystem 1706 mounted on the optical bench, and including 1-D CCD image detection array 1696 having vertically-elongated image detection elements 1707 and being contained within a light-box 1708 provided with image formation optics 1709, through which light collected from the illuminated

object along field of view (FOV) 1695 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 1710A and 1710B mounted on optical bench 1706 on opposite sides of the IFD module 1706, for producing a PLIB 1693 within the FOV 1695; and an optical assembly 1711 configured with each PLIM, including an optically-reflective temporal phase modulating cavity (etalon) 1712 mounted to the outside of each VLD before a cylindrical lens array 1713, to produce a despeckling mechanism that operates in accordance with the third generalized method of speckle-pattern noise reduction illustrated in Figs. 1I17A through 1I17B.

Ninth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Fourth Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I19A And 1I19B

In Fig. 48A, there is shown a ninth illustrative embodiment of the PLIIM-based hand-supportable imager 1720 of the present invention. As shown, the PLIIM-based imager 1720 comprises: a hand-supportable housing 1721; a PLIIM-based image capture and processing engine 1722 contained therein, for projecting a planar laser illumination beam (PLIB) 1723 through its imaging window 1724 in coplanar relationship with the field of view (FOV) 1725 of the linear image detection array 1726 employed in the engine; a LCD display panel 1727 mounted on the upper top surface 1728 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1729 mounted on the middle top surface 1730 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1731, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1732 with a digital communication network 1733, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 48B, the PLIIM-based image capture and processing engine 1722 comprises: an optical-bench/multi-layer PC board 1734, contained between the upper and lower portions of the engine housing 1735A and 1735B; an IFD (i.e. camera) subsystem 1736 mounted on the optical bench, and including 1-D CCD image detection array 1726 having vertically-elongated image detection elements 1726A and being contained within a light-box 1737A provided with image formation optics 1737B, through which light collected from the illuminated object along field of view (FOV) 1725 is permitted to pass; a pair of PLIMs (i.e.

comprising a dual-VLD PLIA) 1738A and 1738B mounted on optical bench 1734 on opposite sides of the IFD module 1736, for producing a PLIB 1723 within the FOV 1725; and an optical assembly configured with each PLIM, including a frequency mode hopping inducing circuit 1739A, and a cylindrical lens array 1739B, to produce a despeckling mechanism that operates in accordance with the fourth generalized method of speckle-pattern noise reduction illustrated in Figs. 1I19A through 1I19B.

<u>Tenth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Fifth Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I21A And 1I21D</u>

In Fig. 49A, there is shown a tenth illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1740 comprises: a hand-supportable housing 1741; a PLIIM-based image capture and processing engine 1742 contained therein, for projecting a planar laser illumination beam (PLIB) 1743 through its imaging window 1744 in coplanar relationship with the field of view (FOV) 1745 of the linear image detection array 1746 employed in the engine; a LCD display panel 1747 mounted on the upper top surface 1748 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1749 mounted on the middle top surface of the housing 1750, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1751, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1752 with a digital communication network 1753, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 49B, the PLIIM-based image capture and processing engine 1742 comprises: an optical-bench/multi-layer PC board 1754, contained between the upper and lower portions of the engine housing 1755A and 1755B; an IFD (i.e. camera) subsystem 1756 mounted on the optical bench, and including 1-D CCD image detection array 1746 having vertically-elongated image detection elements 1757 and being contained within a light-box 1758 provided with image formation optics 1759, through which light collected from the illuminated object along field of view (FOV) 1745 is permitted to pass; a pair of PLIMs 1760A and 1760B (i.e. comprising a dual-VLD PLIA) mounted on optical bench 1756 on opposite sides of the IFD

module, for producing a PLIB 1743 within the FOV 1745; and an optical assembly 1761 configured with each PLIM, including a spatial intensity modulation panel 1762 mounted before a cylindrical lens array 1763, to produce a despeckling mechanism that operates in accordance with the fifth generalized method of speckle-pattern noise reduction illustrated in Figs. 1I21A through 1I21B.

Notably, spatial intensity modulation panel 1762 employed in optical assembly 1761 can be realized in various ways including, for example: reciprocating spatial intensity modulation arrays, in which electrically-passive spatial intensity modulation arrays or screens are reciprocated relative to each other at a high frequency; an electro-optical spatial intensity modulation panel having electrically addressable, vertically-extending pixels which are switched between transparent and opaque states at rates which exceed the inverse of the photo-integration time period of the image detection array employed in the PLIIM-based system; etc.

Eleventh Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Sixth Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I23A And 1I23B

In Fig. 50A, there is shown an eleventh illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1770 comprises: a hand-supportable housing 1771; a PLIIM-based image capture and processing engine 1772 contained therein, for projecting a planar laser illumination beam (PLIB) 1773 through its imaging window 1774 in coplanar relationship with the field of view (FOV) 1775 of the linear image detection array 1776 employed in the engine; a LCD display panel 1777 mounted on the upper top surface 1778 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1779 mounted on the middle top surface 1780 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1781, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1782 with a digital communication network 1783, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 50B, the PLIIM-based image capture and processing engine 1772 comprises: an optical-bench/multi-layer PC board 1784, contained between the upper and

lower portions of the engine housing 1785A and 1785B; an IFD (i.e. camera) subsystem 1786 mounted on the optical bench, and including 1-D CCD image detection array 1776 having vertically-elongated image detection elements 1787 and being contained within a light-box 1788 provided with image formation optics 1789, through which light collected from the illuminated object along field of view (FOV) 1775 is permitted to pass; a pair of PLIMs 1790A and 1790B (i.e. comprising a dual-VLD PLIA) mounted on optical bench 1784 on opposite sides of the IFD module, for producing a PLIB within the FOV; and an optical assembly 1791 configured with each PLIM, including a spatial intensity modulation aperture 1792 mounted before the entrance pupil 1793 of the IFD module 1786, to produce a despeckling mechanism that operates in accordance with the sixth generalized method of speckle-pattern noise reduction illustrated in Figs. 1I23A through 1I23B.

<u>Twelfth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Linear Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Seventh Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Fig. 1I25</u>

In Fig. 51A, there is shown an twelfth illustrative embodiment of the PLIIM-based hand-supportable imager of the present invention. As shown, the PLIIM-based imager 1800 comprises: a hand-supportable housing 1801; a PLIIM-based image capture and processing engine 1802 contained therein, for projecting a planar laser illumination beam (PLIB) 1803 through its imaging window 1804 in coplanar relationship with the field of view (FOV) 1805 of the linear image detection array 1806 employed in the engine; a LCD display panel 1807 mounted on the upper top surface 1808 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1809 mounted on the middle top surface 1810 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1811, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1812 with a digital communication network 1813 , such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 51B, the PLIIM-based image capture and processing engine 1802 comprises: an optical-bench/multi-layer PC board 1813, contained between the upper and lower portions of the engine housing 1814A and 1814B; an IFD (i.e. camera) subsystem 1815

mounted on the optical bench, and including 1-D CCD image detection array 1806 having vertically-elongated image detection elements 1816 and being contained within a light-box 1817 provided with image formation optics 1818, through which light collected from the illuminated object along field of view (FOV) 1805 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 1819A and 1819B mounted on optical bench 1813 on opposite sides of the IFD module, for producing a PLIB 1803 within the FOV 1805; and an optical assembly 1820 configured with each PLIM, including a temporal intensity modulation aperture 1821 mounted before the entrance pupil 1822 of the IFD module, to produce a despeckling mechanism that operates in accordance with the seventh generalized method of speckle-pattern noise reduction illustrated in Fig. 1I25.

First Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I1A Through 1I3A

In Fig. 52A, there is shown a first illustrative embodiment of the PLIIM-based hand-supportable area-type imager of the present invention. As shown, the hand-supportable area imager 1830 comprises: a hand-supportable housing 1831; a PLIIM-based image capture and processing engine 1832 contained therein, for projecting a planar laser illumination beam (PLIB) 1833 through its imaging window 1834 in coplanar relationship with the field of view (FOV) 1835 of the area image detection array 1836 employed in the engine; a LCD display panel 1837 mounted on the upper top surface 1838 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 1839 mounted on the middle top surface 1840 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 1841, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 1842 with a digital communication network 1843, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 52B, the PLIIM-based image capture and processing engine 1832 comprises: an optical-bench/multi-layer PC board 1844, contained between the upper and lower portions of the engine housing 1845A and 1845B; an IFD (i.e. camera) subsystem 1846 mounted on the optical bench, and including 2-D area-type CCD image detection array 1836

contained within a light-box 1847 provided with image formation optics 1848, through which light collected from the illuminated object along 3-D field of view (FOV) 1835 is permitted to pass; a pair of PLIMs 1849A and 1849B (i.e. comprising a dual-VLD PLIA) mounted on optical bench 1844 on opposite sides of the IFD module 1846, for producing a PLIB within the 3-D FOV; a pair of cylindrical lens arrays 1850A and 1850B configured with PLIMs 1849A and 1849B, respectively; a pair of beam sweeping mirrors 1851A and 1851B for sweeping the planar laser illumination beams 1833, from cylindrical lens arrays 1850A and 1850B, respectively, across the 3-D FOV 1835; and an optical assembly 1852 including a temporal intensity modulation panel 1853 mounted before the entrance pupil 1854 of the IFD module, so as to produce a despeckling mechanism that operates in accordance with the seventh generalized method of speckle-pattern noise reduction illustrated in Figs. 1I24 through 1I24C.

<u>System Control Architectures For PLIIM-Based Hand-Supportable Area Imagers Of The Present Invention Employing Area-Type Image Formation And Detection (IFD) Modules</u>

In general, there are a various types of system control architectures (i.e. schemes) that can be used in conjunction with any of the hand-supportable PLIIM-based area-type imagers shown in Figs. 52A through 52B and 54A through 1I64B, and described throughout the present Specification. Also, there are three principally different types of image forming optics schemes that can be used to construct each such PLIIM-based area imager. Thus, it is possible to classify hand-supportable PLIIM-based area imagers into least fifteen different system design categories based on such criterion. Below, these system design categories will be briefly described with reference to Figs. 53A1 through 53C5.

<u>System Control Architectures For PLIIM-Based Hand-Supportable Area Imagers Of The Present Invention Employing Area-Type Image Formation And Detection (IFD) Modules Having A Fixed Focal Length/Fixed Focal Distance Image Formation Optics</u>

In Fig. 53A1, there is shown a manually-activated version of a PLIIM-based area-type imager 1860 as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in fig. 53A1, the PLIIM-based area imager 1860 comprises: a planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 with a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 1863 having an area-type image detection array 1864, fixed focal length/fixed focal distance image formation optics 1865 for providing a fixed 3-D field of view (FOV), an image frame grabber 1866, and an image data buffer 1867; a pair of beam sweeping mechanisms 1868A and 1868B for sweeping the planar laser illumination beam 1869 produced

from the PLIA across the 3-D FOV; an image processing computer 1870; a camera control computer 1871; a LCD panel 1872 and a display panel driver 1873; a touch-type or manually-keyed data entry pad 1874 and a keypad driver 1875; and a manually-actuated trigger switch 1876 for manually activating the planar laser illumination arrays, the area-type image formation and detection (IFD) module, and the image processing computer 1870, via the camera control computer 1871, upon manual activation of the trigger switch 1876. Thereafter, the system control program carried out within the camera control computer 1871 enables: (1) the automatic capture of digital images of objects (i.e. bearing bar code symbols and other graphical indicia) through the fixed focal length/fixed focal distance image formation optics 1865 provided within the area imager; (2) decode–processing of the bar code symbol represented therein; (3) generating symbol character data representative of the decoded bar code symbol; (4) buffering of the symbol character data within the hand-supportable housing or transmitting the same to a host computer system; and thereafter (5) automatically deactivating the subsystem components described above. When using a manually-actuated trigger switch 1876 having a single-stage operation, manually depressing the switch 1876 with a single pull-action will thereafter initiate the above sequence of operations with no further input required by the user.

In an alternative embodiment of the system design shown in Fig. 53A1, manually-actuated trigger switch 1876 would be replaced with a dual-position switch 1876′ having a dual-positions (or stages of operation) so as to further embody the functionalities of both switch 1876 shown in Fig. 53A1 and transmission activation switch 1899 shown in Fig. 53A2. Also, the system would be further provided with a data transfer mechanism 1898 as shown in Fig. 53A2, for example, so that it embodies the symbol character data transmission functions described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. In such an alternative embodiment, when the user pulls the dual-position switch 1876′ to its first position, the camera control computer 1871 will automatically activate the following components: the planar laser illumination array 6 (driven by VLD driver circuits 18), the area-type image formation and detection (IFD) module 1844, and the image processing computer 1870 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically and repeatedly captured, (2) bar code symbols represented therein are repeatedly decoded, and (3) symbol character data representative of each decoded bar code symbol is automatically generated in a cyclical manner (i.e. after each reading of each instance of the bar code symbol) and buffered in the data transmission mechanism 1260. Then, when the user further depresses the dual-position switch to its second position (i.e. complete depression or activation), the camera control computer 1235 enables the data transmission mechanism 1898 to transmit character data from the imager processing computer 1870 to a host computer system

in response to the manual activation of the dual-position switch 1876′ to its second position at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 1870 and buffered in data transmission switch 1898. This dual-stage switching mechanism provides the user with an additional degree of control when trying to accurately read a bar code symbol from a bar code menu, on which two or more bar code symbols reside on a single line of a bar code menu, and width of the FOV of the hand-held imager spatially extends over these bar code symbols, making bar code selection challenging if not difficult.

In Fig. 53A2, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53A2, the PLIIM-based area imager 1880 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 1883 having an area-type image detection array 1884 and fixed focal length/fixed focal distance image formation optics 1885 for providing a fixed 3-D field of view (FOV), an image frame grabber 1886, and an image data buffer 1887; a pair of beam sweeping mechanisms 1888A and 1888B for sweeping the planar laser illumination beam 1889 produced from the PLIA across the 3-D FOV; an image processing computer 1890; a camera control computer 1891; a LCD panel 1892 and a display panel driver 1893; a touch-type or manually-keyed data entry pad 1894 and a keypad driver 1895; an IR-based object detection subsystem 1896 within its hand-supportable housing for automatically activating in response to the detection of an object in its IR-based object detection field 1897, the planar laser illumination array (driven by the VLD driver circuits), the area-type image formation and detection (IFD) module, as well as the image processing computer, via the camera control computer, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 1898 and a manually-activatable data transmission switch 1899 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 1998 in response to the manual activation of the data transmission switch 1899 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In Fig. 53A3, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53A3, the PLIIM-based area imager 2000 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 2001 having an area-type image detection array 2002 and fixed focal length/fixed focal distance image formation optics 2003 for providing a fixed 3-D field of view (FOV), an image frame grabber 2004, and an image data buffer 2005; a pair of beam sweeping mechanisms 2006A and 2006B for sweeping the planar laser illumination beam (PLIB) 2007 produced from the PLIA across the 3-D FOV; an image processing computer 2008; a camera control computer 2009; a LCD panel 2010 and a display panel driver 2011; a touch-type or manually-keyed data entry pad 2012 and a keypad driver 2013; a laser-based object detection subsystem 2014 embodied within the camera control computer for automatically activating the planar laser illumination arrays into a full-power mode of operation, the area-type image formation and detection (IFD) module, and the image processing computer, via the camera control computer, in response to the automatic detection of an object in its laser-based object detection field 2015, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and, data transmission mechanism 2016 and a manually-activatable data transmission switch 2017 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 2016 in response to the manual activation of the data transmission switch 2017 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In the illustrative embodiment of Fig. 40A3, the PLIIM-based system has an object detection mode, a bar code detection mode, and a bar code reading mode of operation, as taught in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, supra. During the object detection mode of operation of the system, the camera control computer 2009 transmits a control signal to the VLD drive circuitry 11, (optionally via the PLIA microcontroller), causing each PLIM to generate a pulsed-type planar laser illumination beam (PLIB) consisting of planar laser light pulses having a very low duty cycle (e.g. as low as 0.1 %) and high repetition frequency (e.g. greater than 1 kHZ), so as to

function as a non-visible PLIB-based object sensing beam (and/or bar code detection beam, as the case may be). Then, when the camera control computer receives an activation signal from the laser-based object detection subsystem 2014 (i.e. indicative that an object has been detected by the non-visible PLIB-based object sensing beam), the system automatically advances to either: (i) its bar code detection state, where it increases the power level of the PLIB, collects image data and performs bar code detection operations, and therefrom, to its bar code symbol reading state, in which the output power of the PLIB is further increased, image data is collected and decode processed; or (ii) directly to its bar code symbol reading state, in which the output power of the PLIB is increased, image data is collected and decode processed. A primary advantage of using a pulsed high-frequency/low-duty-cycle PLIB as an object sensing beam is that it consumes minimal power yet enables image capture for automatic object and/or bar code detection purposes, without distracting the user by visibly blinking or flashing light beams which tend to detract from the user's experience. In yet alternative embodiments, however, it may be desirable to drive the VLD in each PLIM so that a visibly blinking PLIB-based object sensing beam (and/or bar code detection beam) is generated during the object detection (and bar code detection) mode of system operation. The visibly blinking PLIB-based object sensing beam will typically consist of planar laser light pulses having a moderate duty cycle (e.g. 25 %) and low repetition frequency (e.g. less than 30HZ). In this alternative embodiment of the present invention, the low frequency blinking nature of the PLIB-based object sensing beam (and/or bar code detection beam) would be rendered visually conspicuous, thereby facilitating alignment of the PLIB/FOV with the bar code symbol, or graphics being imaged in relatively bright imaging environments.

In Fig. 53A4, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53A4, the PLIIM-based area imager 2020 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 2021 having an area-type image detection array 2022 and fixed focal length/fixed focal distance image formation optics 2023 for providing a fixed 3-D field of view (FOV), an image frame grabber 2024, and an image data buffer 2025; a pair of beam sweeping mechanisms 2026A and 2026B for sweeping the planar laser illumination beam (PLIB) 2027 produced from the PLIA across the 3-D FOV; an image processing computer 2028; a camera control computer 2029; a LCD panel 2030 and a display panel driver 2031; a touch-type or manually-keyed data entry pad 2032 and a keypad driver 2033; an ambient-light driven object detection subsystem 2034 within its hand-supportable housing for automatically activating the planar laser illumination array 6 (driven by VLD driver circuits), the area-type image formation and

detection (IFD) module, and the image processing computer, via the camera control computer, in response to the automatic detection of an object via ambient-light detected by object detection field enabled by the area image sensor within the IFD module 2021, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 2035 and a manually-activatable data transmission switch 2036 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 2035, in response to the manual activation of the data transmission switch 2036 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. Notably, in some applications, the passive-mode objection detection subsystem 2034 employed in this system might require (i) using a different system of optics for collecting ambient light from objects during the object detection mode of the system, or (ii) modifying the light collection characteristics of the light collection system to permit increased levels of ambient light to be focused onto the CCD image detection array 2022 in the IFD module (i.e. subsystem). In other applications, the provision of image intensification optics on the surface of the CCD image detection array should be sufficient to form images of sufficient brightness to perform object detection and/or bar code detection operations.

In Fig. 53A5, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53A5, the PLIIM-based linear imager 2040 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 2041 having an area-type image detection array 2042 and fixed focal length/fixed focal distance image formation optics 2043 for providing a fixed 3-D field of view (FOV), an image frame grabber 2044, and an image data buffer 2045; a pair of beam sweeping mechanisms 2046A and 2046B for sweeping the planar laser illumination beam (PLIB) 2047 produced from the PLIA across the 3-D FOV; an image processing computer 2048; a camera control computer 2049; a LCD panel 2050 and a display panel driver 2051; a touch-type or manually-keyed data entry pad 2052 and a keypad driver 2053; an automatic bar code symbol detection subsystem 2054 within its hand-supportable housing for automatically activating the image processing

computer for decode-processing upon automatic detection of a bar code symbol within its bar code symbol detection field 2055 by the area image sensor within the IFD module 2041 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 2056 and a manually-activatable data transmission switch 2057 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 2056, in response to the manual activation of the data transmission switch 2057 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

<u>System Control Architectures For PLIIM-Based Hand-Supportable Area Imagers Of The Present Invention Employing Area-Type Image Formation And Detection (IFD) Modules Having Fixed Focal Length/Variable Focal Distance Image Formation Optics</u>

In Fig. 53B1, there is shown a manually-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53B1, the PLIIM-based linear imager 2060 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 2061 having an area-type image detection array 2062 and fixed focal length/variable focal distance image formation optics 2063 for providing a fixed 3-D field of view (FOV), an image frame grabber 2064, and an image data buffer 2065; a pair of beam sweeping mechanisms 2066A and 2066B for sweeping the planar laser illumination beam (PLIB) 2067 produced from the PLIA across the 3-D FOV; an image processing computer 2068; a camera control computer 2069; a LCD panel 2070 and a display panel driver 2071; a touch-type or manually-keyed data entry pad 2072 and a keypad driver 2073; and a manually-actuated trigger switch 2074 for manually activating the planar laser illumination arrays, the area-type image formation and detection (IFD) module, the image frame grabber, the image data buffer, and the image processing computer, via the camera control computer, upon manual activation of the trigger switch 2074. Thereafter, the system control program carried out within the camera control computer 2069 enables: (1) the automatic capture of digital images of objects (i.e. bearing bar code symbols and other graphical indicia) through the fixed focal length/fixed focal

distance image formation optics 2063 provided within the area imager; (2) decode-processing the bar code symbol represented therein; (3) generating symbol character data representative of the decoded bar code symbol; (4) buffering the symbol character data within the hand-supportable housing or transmitting the same to a host computer system; and (5) thereafter automatically deactivating the subsystem components described above. When using a manually-actuated trigger switch 2074 having a single-stage operation, manually depressing the switch 2074 with a single pull-action will thereafter initiate the above sequence of operations with no further input required by the user.

In an alternative embodiment of the system design shown in Fig. 53B1, manually-actuated trigger switch 2074 would be replaced with a dual-position switch 2074′ having a dual-positions (or stages of operation) so as to further embody the functionalities of both switch 2074 shown in Fig. 53B1 and transmission activation switch 2097 shown in Fig. 53A2. Also, the system would be further provided with a data transfer mechanism 2096 as shown in Fig. 53A2, for example, so that it embodies the symbol character data transmission functions described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. In such an alternative embodiment, when the user pulls the dual-position switch 2074′ to its first position, the camera control computer 2069 will automatically activate the following components: the planar laser illumination array 6 (driven by VLD driver circuits 18), the area-type image formation and detection (IFD) module 2062, and the image processing computer 2068 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically and repeatedly captured, (2) bar code symbols represented therein are repeatedly decoded, and (3) symbol character data representative of each decoded bar code symbol is automatically generated in a cyclical manner (i.e. after each reading of each instance of the bar code symbol) and buffered in the data transmission mechanism 2096. Then, when the user further depresses the dual-position switch to its second position (i.e. complete depression or activation), the camera control computer 2069 enables the data transmission mechanism 2096 to transmit character data from the imager processing computer 2068 to a host computer system in response to the manual activation of the dual-position switch 2074′ to its second position at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 2068 and buffered in data transmission switch 2074′. This dual-stage switching mechanism provides the user with an additional degree of control when trying to accurately read a bar code symbol from a bar code menu, on which two or more bar code symbols reside on a single line of a bar code menu, and width of the FOV of the hand-held imager spatially extends over these bar code symbols, making bar code selection challenging if not difficult.

In Fig. 53B2, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53B2, the PLIIM-based area imager 2080 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 2081 having an area-type image detection array 2082 and fixed focal length/variable focal distance image formation optics 2083 for providing a fixed 3-D field of view (FOV), an image frame grabber 2084 and an image data buffer 2085; a pair of beam sweeping mechanisms 2086A and 2086B for sweeping the planar laser illumination beam (PLIB) 2087 produced from the PLIA across the 3-D FOV; an image processing computer 2088; a camera control computer 2089; a LCD panel 2090 and a display panel driver 2091; a touch-type or manually-keyed data entry pad 2092 and a keypad driver 2093; an IR-based object detection subsystem 2094 within its hand-supportable housing for automatically activating upon detection of an object in its IR-based object detection field 2095, the planar laser illumination array (driven by VLD driver circuits), the area-type image formation and detection (IFD) module, as well as and the image processing computer, via the camera control computer, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 2096 and a manually-activatable data transmission switch 2097 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 2096, in response to the manual activation of the data transmission switch 2097 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In Fig. 53B3, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53B3, the PLIIM-based linear imager comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 3001 having an area-type image detection array 3002 and fixed focal length/variable focal distance image formation optics 3003 providing a fixed 3-D field of view (FOV, an image frame grabber 3004, and an image data buffer 3005; a pair of beam sweeping

mechanisms 3006A and 3006B for sweeping the planar laser illumination beam (PLIB) 3007 produced from the PLIA across the 3-D FOV; an image processing computer 3008; a camera control computer 3009; a LCD panel 3010 and a display panel driver 3011; a touch-type or manually-keyed data entry pad 3012 and a keypad driver 3013; a laser-based object detection subsystem 3013 within its hand-supportable housing for automatically activating the planar laser illumination arrays into a full-power mode of operation, the area-type image formation and detection (IFD) module, and the image processing computer, via the camera control computer, upon automatic detection of an object in its laser-based object detection field 3014, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 3015 and a manually-activatable data transmission switch 3016 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 3015 in response to the manual activation of the data transmission switch 3016 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In the illustrative embodiment of Fig. 53B3, the PLIIM-based system has an object detection mode, a bar code detection mode, and a bar code reading mode of operation, as taught in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, supra. During the object detection mode of operation of the system, the camera control computer 3009 transmits a control signal to the VLD drive circuitry 11, (optionally via the PLIA microcontroller), causing each PLIM to generate a pulsed-type planar laser illumination beam (PLIB) consisting of planar laser light pulses having a very low duty cycle (e.g. as low as 0.1 %) and high repetition frequency (e.g. greater than 1 kHZ), so as to function as a non-visible PLIB-based object sensing beam (and/or bar code detection beam, as the case may be). Then, when the camera control computer receives an activation signal from the laser-based object detection subsystem 3013 (i.e. indicative that an object has been detected by the non-visible PLIB-based object sensing beam), the system automatically advances to either: (i) its bar code detection state, where it increases the power level of the PLIB, collects image data and performs bar code detection operations, and therefrom, to its bar code symbol reading state, in which the output power of the PLIB is further increased, image data is collected and decode processed; or (ii) directly to its bar code symbol reading state, in which the

output power of the PLIB is increased, image data is collected and decode processed. A primary advantage of using a pulsed high-frequency/low-duty-cycle PLIB as an object sensing beam is that it consumes minimal power yet enables image capture for automatic object and/or bar code detection purposes, without distracting the user by visibly blinking or flashing light beams which tend to detract from the user's experience. In yet alternative embodiments, however, it may be desirable to drive the VLD in each PLIM so that a visibly blinking PLIB-based object sensing beam (and/or bar code detection beam) is generated during the object detection (and bar code detection) mode of system operation. The visibly blinking PLIB-based object sensing beam will typically consist of planar laser light pulses having a moderate duty cycle (e.g. 25 %) and low repetition frequency (e.g. less than 30HZ). In this alternative embodiment of the present invention, the low frequency blinking nature of the PLIB-based object sensing beam (and/or bar code detection beam) would be rendered visually conspicuous, thereby facilitating alignment of the PLIB/FOV with the bar code symbol, or graphics being imaged in relatively bright imaging environments.

In Fig. 53B4, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53B4, the PLIIM-based area imager 3020 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 3021 having an area-type image detection array 3022 and fixed focal length/variable focal distance image formation optics 3023 for providing a fixed 3-D field of view (FOV), an image frame grabber 3024, and an image data buffer 3025; a pair of beam sweeping mechanisms 3026A and 3026B for sweeping the planar laser illumination beam (PLIB) 3027 produced from the PLIA across the 3-D FOV; an image processing computer 3028; a camera control computer 3029; a LCD panel 3030 and a display panel driver 3031; a touch-type or manually-keyed data entry pad 3032 and a keypad driver 3033; an ambient-light driven object detection subsystem 3034 within its hand-supportable housing for automatically activating the planar laser illumination array (driven by VLD driver circuits), the area-type image formation and detection (IFD) module, and the image processing computer, via the camera control computer, in response to the automatic detection of an object via ambient-light detected by object detection field 3035 enabled by the area image sensor 3022 within the IFD module, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 3036 and a manually-activatable data transmission switch 3037 for enabling the transmission of symbol character data from the

imager processing computer to a host computer system, via the data transmission mechanism 3036, in response to the manual activation of the data transmission switch 3037 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. Notably, in some applications, the passive-mode objection detection subsystem 3034 employed in this system might require (i) using a different system of optics for collecting ambient light from objects during the object detection mode of the system, or (ii) modifying the light collection characteristics of the light collection system to permit increased levels of ambient light to be focused onto the CCD image detection array 3022 in the IFD module (i.e. subsystem). In other applications, the provision of image intensification optics on the surface of the CCD image detection array should be sufficient to form images of sufficient brightness to perform object detection and/or bar code detection operations.

In Fig. 53B5, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53B5, the PLIIM-based area imager 3040 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 3041 having an area-type image detection array 3042 and fixed focal length/variable focal distance image formation optics 3043 for providing a fixed 3-D field of view (FOV), an image frame grabber 3044, and an image data buffer 3045; a pair of beam sweeping mechanisms 3046A and 3046B for sweeping the planar laser illumination beam (PLIB) 3047 produced from the PLIA across the 3-D FOV; an image processing computer 3048; a camera control computer 3049; a LCD panel 3050 and a display panel driver 3051; a touch-type or manually-keyed data entry pad 3052 and a keypad driver 3053; an automatic bar code symbol detection subsystem 3054 within its hand-supportable housing for automatically activating the image processing computer for decode-processing upon automatic detection of a bar code symbol within its bar code symbol detection field 3055 by the linear image sensor 3042 within the IFD module so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 3056 and a manually-activatable data transmission switch 3057 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism

3056, in response to the manual activation of the data transmission switch 3057 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

System Control Architectures For PLIIM-Based Hand-Supportable Linear Imagers Of The Present Invention Employing Linear-Type Image Formation And Detection (IFD) Modules Having Variable Focal Length/Variable Focal Distance Image Formation Optics

In Fig. 53C1, there is shown a manually-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53C1, the PLIIM-based area imager 3060 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 3061 having an area-type image detection array 3062 and variable focal length/variable focal distance image formation optics 3063 for providing a variable 3-D field of view (FOV), an image frame grabber 3064, and an image data buffer 3065; a pair of beam sweeping mechanisms 3066A and 3066B for sweeping the planar laser illumination beam (PLIB) 3067 produced from the PLIA across the 3-D FOV; an image processing computer 3068; a camera control computer 3069; a LCD panel 3070 and a display panel driver 3071; a touch-type or manually-keyed data entry pad 3072 and a keypad driver 3073; and a manually-actuated trigger switch 3074 for manually activating the planar laser illumination arrays, the area-type image formation and detection (IFD) module, and the image processing computer, via the camera control computer, in response to the manual activation of the trigger switch 3074. Thereafter, the system control program carried out within the camera control computer 3069 enables: (1) the automatic capture of digital images of objects (i.e. bearing bar code symbols and other graphical indicia) through the fixed focal length/fixed focal distance image formation optics 3063 provided within the area imager; (2) decode–processing the bar code symbol represented therein; (3) generating symbol character data representative of the decoded bar code symbol; (4) buffering the symbol character data within the hand-supportable housing or transmitting the same to a host computer system; and (5) thereafter automatically deactivating the subsystem components described above. When using a manually-actuated trigger switch 3074 having a single-stage operation, manually depressing the switch 3074 with a single pull-action will thereafter initiate the above sequence of operations with no further input required by the user.

In an alternative embodiment of the system design shown in Fig. 53C1, manually-actuated trigger switch 3074 would be replaced with a dual-position switch 3074′ having a dual-positions (or stages of operation) so as to further embody the functionalities of both switch 3074′ shown in Fig. 53C1 and transmission activation switch 3097 shown in Fig. 53C2. Also, the system would be further provided with a data transfer mechanism 3096 as shown in Fig. 53C2, for example, so that it embodies the symbol character data transmission functions described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. In such an alternative embodiment, when the user pulls the dual-position switch 3074′ to its first position, the camera control computer 3069 will automatically activate the following components: the planar laser illumination array 6 (driven by VLD driver circuits 18), the linear-type image formation and detection (IFD) module 3062, and the image processing computer 3068 so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically and repeatedly captured, (2) bar code symbols represented therein are repeatedly decoded, and (3) symbol character data representative of each decoded bar code symbol is automatically generated in a cyclical manner (i.e. after each reading of each instance of the bar code symbol) and buffered in the data transmission mechanism 3096. Then, when the user further depresses the dual-position switch to its second position (i.e. complete depression or activation), the camera control computer 3069 enables the data transmission mechanism 3096 to transmit character data from the imager processing computer 3068 to a host computer system in response to the manual activation of the dual-position switch 3074′ to its second position at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer 3068 and buffered in data transmission switch 3097. This dual-stage switching mechanism provides the user with an additional degree of control when trying to accurately read a bar code symbol from a bar code menu, on which two or more bar code symbols reside on a single line of a bar code menu, and width of the FOV of the hand-held imager spatially extends over these bar code symbols, making bar code selection challenging if not difficult.

In Fig. 53C2, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53C2, the PLIIM-based area imager 3080 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 3081 having an area-type image detection array 3082 and variable focal length/variable focal distance image formation optics 3083 for providing a variable 3-D field of view (FOV), an image frame grabber 3084, and an image data buffer 3085; a pair of beam

sweeping mechanisms 3086A and 3086B for sweeping the planar laser illumination beam (PLIB) 3087 produced from the PLIA across the 3-D FOV; an image processing computer 3088; a camera control computer 3089; a LCD panel 3090 and a display panel driver 3091; a touch-type or manually-keyed data entry pad 3092 and a keypad driver 3093; an IR-based object detection subsystem 3094 within its hand-supportable housing for automatically activating upon detection of an object in its IR-based object detection field 3095, the planar laser illumination array (driven by VLD driver circuits), the area-type image formation and detection (IFD) module, as well as and the image processing computer, via the camera control computer, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 3096 and a manually-activatable data transmission switch 3097 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 3096, in response to the manual activation of the data transmission switch 3097 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In Fig. 53C3, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53C3, the PLIIM-based area imager 4000 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 4001 having an area-type image detection array 4002 and variable focal length/variable focal distance image formation optics 4003 for providing a variable 3-D field of view (FOV), an image frame grabber 4004, and an image data buffer 4005; a pair of beam sweeping mechanisms 4006A and 4006B for sweeping the planar laser illumination beam (PLIB) 4007 produced from the PLIA across the 3-D FOV; an image processing computer 4008; a camera control computer 4009; a LCD panel 4010 and a display panel driver 4011; a touch-type or manually-keyed data entry pad 4012 and a keypad driver 4013; a laser-based object detection subsystem 4014 within its hand-supportable housing for automatically activating the planar laser illumination arrays into a full-power mode of operation, the area-type image formation and detection (IFD) module, and the image processing computer, via the camera control computer, in response to the automatic detection of an object in its laser-based object detection

field 4015, so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 4016 and a manually-activatable data transmission switch 4017 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 4016, in response to the manual activation of the data transmission switch 4017 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

In the illustrative embodiment of Fig. 53C3, the PLIIM-based system has an object detection mode, a bar code detection mode, and a bar code reading mode of operation, as taught in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, supra. During the object detection mode of operation of the system, the camera control computer 4009 transmits a control signal to the VLD drive circuitry 11, (optionally via the PLIA microcontroller), causing each PLIM to generate a pulsed-type planar laser illumination beam (PLIB) consisting of planar laser light pulses having a very low duty cycle (e.g. as low as 0.1 %) and high repetition frequency (e.g. greater than 1 kHZ), so as to function as a non-visible PLIB-based object sensing beam (and/or bar code detection beam, as the case may be). Then, when the camera control computer receives an activation signal from the laser-based object detection subsystem 4014 (i.e. indicative that an object has been detected by the non-visible PLIB-based object sensing beam), the system automatically advances to either: (i) its bar code detection state, where it increases the power level of the PLIB, collects image data and performs bar code detection operations, and therefrom, to its bar code symbol reading state, in which the output power of the PLIB is further increased, image data is collected and decode processed; or (ii) directly to its bar code symbol reading state, in which the output power of the PLIB is increased, image data is collected and decode processed. A primary advantage of using a pulsed high-frequency/low-duty-cycle PLIB as an object sensing beam is that it consumes minimal power yet enables image capture for automatic object and/or bar code detection purposes, without distracting the user by visibly blinking or flashing light beams which tend to detract from the user's experience. In yet alternative embodiments, however, it may be desirable to drive the VLD in each PLIM so that a visibly blinking PLIB-based object sensing beam (and/or bar code detection beam) is generated during the object detection (and bar code detection) mode of system operation. The visibly blinking PLIB-based object sensing

beam will typically consist of planar laser light pulses having a moderate duty cycle (e.g. 25 %) and low repetition frequency (e.g. less than 30HZ). In this alternative embodiment of the present invention, the low frequency blinking nature of the PLIB-based object sensing beam (and/or bar code detection beam) would be rendered visually conspicuous, thereby facilitating alignment of the PLIB/FOV with the bar code symbol, or graphics being imaged in relatively bright imaging environments.

In Fig. 53C4, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53C4, the PLIIM-based area imager 4020 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 4021 having an area-type image detection array 4022 and variable focal length/variable focal distance image formation optics 4023 providing a variable 3-D field of view (FOV), an image frame grabber 4024, and an image data buffer 4025; a pair of beam sweeping mechanisms 4026A and 4026B for sweeping the planar laser illumination beam (PLIB) 4027 produced from the PLIA across the 3-D FOV; an image processing computer 4028; a camera control computer 4029; a LCD panel 4030 and a display panel driver 4031; a touch-type or manually-keyed data entry pad 4032 and a keypad driver 4033; an ambient-light driven object detection subsystem 4034 within its hand-supportable housing for automatically activating the planar laser illumination array (driven by VLD driver circuits), the area-type image formation and detection (IFD) module, and the image processing computer, via the camera control computer, in response to the automatic detection of an object via ambient-light detected by object detection field 4035 enabled by the area image sensor 4022 within the IFD module so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and data transmission mechanism 4036 and a manually-activatable data transmission switch 4037 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 4036, in response to the manual activation of the data transmission switch 4037 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety. Notably, in some applications, the passive-mode objection detection subsystem 4034 employed in this

system might require (i) using a different system of optics for collecting ambient light from objects during the object detection mode of the system, or (ii) modifying the light collection characteristics of the light collection system to permit increased levels of ambient light to be focused onto the CCD image detection array 4022 in the IFD module (i.e. subsystem). In other applications, the provision of image intensification optics on the surface of the CCD image detection array should be sufficient to form images of sufficient brightness to perform object detection and/or bar code detection operations.

In Fig. 53C5, there is shown an automatically-activated version of the PLIIM-based area imager as illustrated, for example, in Figs. 52A through 52B and 54A through 64B. As shown in Fig. 53C5, the PLIIM-based area imager 4040 comprises: planar laser illumination array (PLIA) 6, including a set of VLD driver circuits 18, PLIMs 11, an integrated despeckling mechanism 1861 having a stationary cylindrical lens array 1862; an area-type image formation and detection (IFD) module 4041 having an area-type image detection array 4042 and variable focal length/variable focal distance image formation optics 4043 for providing a variable 3-D field of view (FOV), an image frame grabber 4044, an image data buffer 4045; a pair of beam sweeping mechanisms 4046A and 4046B for sweeping the planar laser illumination beam (PLIB) 4047 produced from the PLIA across the 3-D FOV; an image processing computer 4048; a camera control computer 4049; a LCD panel 4050 and a display panel driver 4051; a touch-type or manually-keyed data entry pad 4052 and a keypad driver 4053; an automatic bar code symbol detection subsystem 4054 within its hand-supportable housing for automatically activating the image processing computer for decode-processing in response to the automatic detection of a bar code symbol within its bar code symbol detection field 4055 by the area image sensor 4042 within the IFD module so that (1) digital images of objects (i.e. bearing bar code symbols and other graphical indicia) are automatically captured, (2) bar code symbols represented therein are decoded, and (3) symbol character data representative of the decoded bar code symbol are automatically generated; and a data transmission mechanism 4056 and a manually-activatable data transmission switch 4057 for enabling the transmission of symbol character data from the imager processing computer to a host computer system, via the data transmission mechanism 4056, in response to the manual activation of the data transmission switch 4057 at about the same time as when a bar code symbol is automatically decoded and symbol character data representative thereof is automatically generated by the image processing computer. This manually-activated symbol character data transmission scheme is described in greater detail in copending US Application Nos. 08/890,320, filed July 9, 1997, and 09/513,601, filed February 25, 2000, each said application being incorporated herein by reference in its entirety.

<u>Second Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I12G And 1I12H</u>

In Fig. 54A, there is shown a second illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4060 comprises: a hand-supportable housing 4061; a PLIIM-based image capture and processing engine 4062 contained therein, for projecting a planar laser illumination beam (PLIB) 4063 through its imaging window 4064 in coplanar relationship with the 3-D field of view (FOV) 4065 of the area image detection array 4066 employed in the engine; a LCD display panel 4067 mounted on the upper top surface 4068 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4069 mounted on the middle top surface 4070 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4071, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4072 with a digital communication network 4073, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 54B, the PLIIM-based image capture and processing engine 4062 comprises: an optical-bench/multi-layer PC board 4075, contained between the upper and lower portions of the engine housing 4076A and 4076B; an IFD module (i.e. camera subsystem) 4077 mounted on the optical bench, and including area CCD image detection array 4066 contained within a light-box 4078 provided with image formation optics 4079, through which light collected from the illuminated object along the 3-D field of view (FOV) 4065 is permitted to pass; a pair of PLIMs (i.e. comprising a dual-VLD PLIA) 4080A and 4080B mounted on optical bench 4075 on opposite sides of the IFD module, for producing PLIB 4063 within the 3-D FOV 4065; a pair of beam sweeping mechanisms 4081A and 4081B for sweeping the planar laser illumination beam (PLIB) 4063 produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM, including a micro-oscillating light reflective element 4082 and a cylindrical lens array 4083 which provides a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I5A through 1I5D.

Third Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I12G And 1I12H

In Fig. 55A, there is shown a third illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4090 comprises: a hand-supportable housing 4091; a PLIIM-based image capture and processing engine 4092 contained therein, for projecting a planar laser illumination beam (PLIB) 4093 through its imaging window 4094 in coplanar relationship with the 3-D field of view (FOV) 4095 of the area image detection array 4096 employed in the engine; a LCD display panel 4097 mounted on the upper top surface 4098 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4099 mounted on the middle top surface 4100 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4101, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4102 with a digital communication network 4103, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 55B, the PLIIM-based image capture and processing engine 4092 comprises: an optical-bench/multi-layer PC board 4104, contained between the upper and lower portions of the engine housing 4105A and 4105B; an IFD (i.e. camera) subsystem 4106 mounted on the optical bench, and including area CCD image detection array 4096 contained within a light-box 4107 provided with image formation optics 4108, through which light collected from the illuminated object along 3-D field of view (FOV) 4095 is permitted to pass; a pair of PLIMs (i.e. single VLD PLIAs) 4109A and 4109B mounted on optical bench 4104 on opposite sides of the IFD module, for producing a PLIB within the 3-D FOV; a pair of beam sweeping mechanisms 4110A and 4110B for sweeping the planar laser illumination beam (PLIB) 4093 produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM, including an acousto-electric Bragg cell structure 4111 and a cylindrical lens array 4112, arranged above the PLIM in the named order, which provides a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I6A and 1I6B.

Fourth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I7A Through 1I17C

In Fig. 56A, there is shown a fourth illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4120 comprises: a hand-supportable housing 4121; a PLIIM-based image capture and processing engine 4122 contained therein, for projecting a planar laser illumination beam (PLIB) 4123 through its imaging window 4124 in coplanar relationship with the field of view (FOV) 4125 of the area image detection array 4126 employed in the engine; a LCD display panel 4127 mounted on the upper top surface 4128 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4129 mounted on the middle top surface of the housing 4130, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4131, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4132 with a digital communication network 4133, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 56B, the PLIIM-based image capture and processing engine 4122 comprises: an optical-bench/multi-layer PC board 4134, contained between the upper and lower portions of the engine housing 4135A and 4135B; an IFD (i.e. camera) subsystem 4136 mounted on the optical bench, and including an area CCD image detection array 4126 contained within a light-box 4137 provided with image formation optics 4138, through which light collected from the illuminated object along the 3-D field of view (FOV) 4125 is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4139A and 4139B mounted on optical bench 4134 on opposite sides of the IFD module, for producing PLIB 4123 within the 3-D FOV 4125; a pair of beam sweeping mechanisms 4140A and 4140 for sweeping the planar laser illumination beam (PLIB) 4123 produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM, including a high spatial-resolution piezo-electric driven deformable mirror (DM) structure 4141 and a cylindrical lens array 4142 mounted upon each PLIM in the named order, providing a despeckling mechanism that operates in accordance with the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I7A through 1I7C.

Fifth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The First Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I8F And 1I18G

In Fig. 57A, there is shown a fifth illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4150 comprises: a hand-supportable housing 4151; a PLIIM-based image capture and processing engine 4152 contained therein, for projecting a planar laser illumination beam (PLIB) 4153 through its imaging window 4154 in coplanar relationship with the 3-D field of view (FOV) 4154 of the area image detection array 4156 employed in the engine; a LCD display panel 4157 mounted on the upper top surface 4158 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4159 mounted on the middle top surface 4160 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4161, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4162 with a digital communication network 4163, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 57B, the PLIIM-based image capture and processing engine 5152 comprises: an optical-bench/multi-layer PC board 4164, contained between the upper and lower portions of the engine housing 4165A and 4165B; an IFD (i.e. camera) subsystem 4166 mounted on the optical bench, and including area CCD image detection array 4156 contained within a light-box 4167 provided with image formation optics 4168, through which light collected from the illuminated object along the 3-D field of view (FOV) 4155 is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4169A and 4169B mounted on optical bench 4164 on opposite sides of the IFD module, for producing PLIB 4153 within the 3-D FOV 4155; a pair of beam sweeping mechanisms 4170A and 4170B for sweeping the planar laser illumination beam (PLIB) produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM, including a spatial-only liquid crystal display (PO-LCD)type spatial phase modulation panel 4071 and a cylindrical lens array 4172 mounted beyond each PLIM in the named order, providing a despeckling mechanism that operates in accordance with

the first generalized method of speckle-pattern noise reduction illustrated in Figs. 1I8F and 1I8G.

<u>Sixth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Second Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I14A Through 1I14D</u>

In Fig. 58A, there is shown a sixth illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4180 comprises: a hand-supportable housing 4181; a PLIIM-based image capture and processing engine 4182 contained therein, for projecting a planar laser illumination beam (PLIB) 4183 through its imaging window 4184 in coplanar relationship with the field of view (FOV) 4185 of the area image detection array 4186 employed in the engine; a LCD display panel 4187 mounted on the upper top surface 4188 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4189 mounted on the middle top surface 4190 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4191, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4192 with a digital communication network 4193, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 58B, the PLIIM-based image capture and processing engine 4182 comprises: an optical-bench/multi-layer PC board 4194, contained between the upper and lower portions of the engine housing 4195A and 4195B; an IFD (i.e. camera) subsystem 4196 mounted on the optical bench, and including an area CCD image detection array 4186 contained within a light-box 4197 provided with image formation optics 4198, through which light collected from the illuminated object along 3-D field of view (FOV) 4185 is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4199A and 4199B mounted on optical bench 4194 on opposite sides of the IFD module, for producing PLIB 4193 within the 3-D FOV 4195; a pair of beam sweeping mechanisms 4200A and 4200B for sweeping the planar laser illumination beam (PLIB) produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM , including a high-speed optical shutter panel 4201 and a cylindrical lens array 4202 mounted before each PLIM, to provide a despeckling mechanism that operates

in accordance with the second generalized method of speckle-pattern noise reduction illustrated in Figs. 1I14A and 1I14B.

Seventh Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Second Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I15A And 1I15B

In Fig. 59A, there is shown a seventh illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4210 comprises: a hand-supportable housing 4211; a PLIIM-based image capture and processing engine 4212 contained therein, for projecting a planar laser illumination beam (PLIB) 4213 through its imaging window 4214 in coplanar relationship with the field of view (FOV) 4215 of the area image detection array 4216 employed in the engine; a LCD display panel 4217 mounted on the upper top surface 4218 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4219 mounted on the middle top surface 4220 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4221, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4222 with a digital communication network 4223, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 59B, the PLIIM-based image capture and processing engine 4212 comprises: an optical-bench/multi-layer PC board 4224, contained between the upper and lower portions of the engine housing 4225A and 4225B; an IFD (i.e. camera) subsystem 4226 mounted on the optical bench, and including an area CCD image detection array 4216 contained within a light-box 4227 provided with image formation optics 4228, through which light collected from the illuminated object along the 3-D field of view (FOV) 4215 is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4229A and 4229B mounted on optical bench 4224 on opposite sides of the IFD module, for producing a PLIB within the 3-D FOV 4215; a pair of beam sweeping mechanisms 4230A and 4230B for sweeping the planar laser illumination beam (PLIB) produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM, including a visible mode locked laser diode (MLLD) 4231 within each PLIM and a cylindrical lens array 4232 after each PLIM, to provide a despeckling

mechanism that operates in accordance with the second generalized method of speckle-pattern noise reduction illustrated in Figs. 1I14A and 1I14B.

Eighth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Third Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I17A And 1I17C

In Fig. 60A, there is shown an eighth illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4240 comprises: a hand-supportable housing 4241; a PLIIM-based image capture and processing engine 4242 contained therein, for projecting a planar laser illumination beam (PLIB) 4243 through its imaging window 4244 in coplanar relationship with the field of view (FOV) 4245 of the area image detection array 4246 employed in the engine; a LCD display panel 4247 mounted on the upper top surface 4248 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4249 mounted on the middle top surface 4250 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4251, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4252 with a digital communication network 4253, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 60B, the PLIIM-based image capture and processing engine 4242 comprises: an optical-bench/multi-layer PC board 4253, contained between the upper and lower portions of the engine housing 4255A and 4255B; an IFD (i.e. camera) subsystem 4256 mounted on the optical bench, and including an area CCD image detection array 4246 contained within a light-box 4257 provided with image formation optics 4258, through which light collected from the illuminated object along the 3-D field of view (FOV) 4245 is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4259A and 4259B mounted on optical bench 4254 on opposite sides of the IFD module, for producing the 4253 PLIB within the 3-D FOV 4245; a pair of beam sweeping mechanisms 4260A and 4260B for sweeping the planar laser illumination beam (PLIB) produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM, including an electrically-passive optically-resonant cavity (i.e. etalon) 4261 mounted external to each VLD and a cylindrical lens array 4262 mounted

beyond the PLIM, to provide a despeckling mechanism that operates in accordance with the third generalized method of speckle-pattern noise reduction illustrated in Figs. 1I17A and 1I17B.

Ninth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Fourth Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I19A And 1I19B

In Fig. 61A, there is shown a ninth illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4290 comprises: a hand-supportable housing 4291; a PLIIM-based image capture and processing engine 4292 contained therein, for projecting a planar laser illumination beam (PLIB) 4293 through its imaging window 4294 in coplanar relationship with the field of view (FOV) 4295 of the area image detection array 4296 employed in the engine; a LCD display panel 4297 mounted on the upper top surface 4298 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4299 mounted on the middle top surface 4300 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4301, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4302 with a digital communication network 4303, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 61B, the PLIIM-based image capture and processing engine 4292 comprises: an optical-bench/multi-layer PC board 4304, contained between the upper and lower portions of the engine housing 4305A and 4305B; an IFD module (i.e. camera subsystem) 4306 mounted on the optical bench, and including an area CCD image detection array 4296 contained within a light-box 4307 provided with image formation optics 4308, through which light collected from the illuminated object along a 3-D field of view (FOV) is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4309A and 4309B mounted on optical bench 4304 on opposite sides of the IFD module, for producing a PLIB within the 3-D FOV; a pair of beam sweeping mechanisms 4310A and 4310B for sweeping the planar laser illumination beam produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM , including mode-hopping VLD drive circuitry 4311 associated with the driver

circuit of each VLD, and a cylindrical lens array 4312 mounted before each PLIM, to provide a despeckling mechanism that operates in accordance with the fourth generalized method of speckle-pattern noise reduction illustrated in Figs. 1I19A and 1I19B.

<u>Tenth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Fifth Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I21A Through 1I21D</u>

In Fig. 62A, there is shown a tenth illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4320 comprises: a hand-supportable housing 4320; a PLIIM-based image capture and processing engine 4322 contained therein, for projecting a planar laser illumination beam (PLIB) 4323 through its imaging window 4324 in coplanar relationship with the field of view (FOV) 4325 of the area image detection array 4326 employed in the engine; a LCD display panel 4327 mounted on the upper top surface 4328 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4329 mounted on the middle top surface 4330 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4331, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4332 with a digital communication network 4333, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 62B, the PLIIM-based image capture and processing engine 4322 comprises: an optical-bench/multi-layer PC board 4334, contained between the upper and lower portions of the engine housing 4335A and 4335B; an IFD (i.e. camera) subsystem 4336 mounted on the optical bench, and including area CCD image detection array 4326 contained within a light-box 4337 provided with image formation optics 4338, through which light collected from the illuminated object along the 3-D field of view (FOV) 4325 is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4339A and 4339B mounted on optical bench 4334 on opposite sides of the IFD module, for producing the PLIB 4323 within the 3-D FOV 4325; a pair of beam sweeping mechanisms 4340A and 4340B for sweeping the planar laser illumination beam (PLIB) produced from the PLIA across the 3-D FOV; and an optical assembly configured with each PLIM , including a micro-oscillating spatial intensity

modulation panel 4341 and a cylindrical lens array 4341 mounted beyond the PLIM in the named order, to provide a despeckling mechanism that operates in accordance with the fifth generalized method of speckle-pattern noise reduction illustrated in Figs. 1I21A through 1I21D.

In an alternative embodiment, micro-oscillating spatial intensity modulation panel 4541 can be replaced by a high-speed electro-optically controlled spatial intensity modulation panel designed to modulate the spatial intensity of the transmitted PLIB and generate a spatial coherence-reduced PLIB for illuminating target objects in accordance with the present invention.

Eleventh Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Sixth Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I22 through 1I23B

In Fig. 63A, there is shown an eleventh illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4350 comprises: a hand-supportable housing 4351; a PLIIM-based image capture and processing engine 4352 contained therein, for projecting a planar laser illumination beam (PLIB) 4353 through its imaging window 4354 in coplanar relationship with the field of view (FOV) 4355 of the area image detection array 4356 employed in the engine; a LCD display panel 4357 mounted on the upper top surface 4358 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4359 mounted on the middle top surface 4360 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4361, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4362 with a digital communication network 4363, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 63B, the PLIIM-based image capture and processing engine 4352 comprises: an optical-bench/multi-layer PC board 4364, contained between the upper and lower portions of the engine housing 4365A and 4365B; an IFD (i.e. camera) subsystem 4366 mounted on the optical bench, and including area CCD image detection array 4356 contained within a light-box 4367 provided with image formation optics 4368, through which light collected from the illuminated object along the 3-D field of view (FOV) 4355 is permitted to

pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4369A and 4369B mounted on optical bench 4364 on opposite sides of the IFD module, for producing the PLIB 4353 within the 3-D FOV 4355; a cylindrical lens array 4370 mounted before each PLIM; a pair of beam sweeping mechanisms 4371A and 4371B for sweeping the planar laser illumination beam (PLIB) produced from the PLIA across the 3-D FOV; and an optical assembly configured with the IFD module 4366, including an electro-optical or mechanically rotating aperture (i.e. iris) 4372 disposed before the entrance pupil of the IFD module, to provide a despeckling mechanism that operates in accordance with the sixth generalized method of speckle-pattern noise reduction illustrated in Figs. 1I22 through 1I23B.

<u>Twelfth Illustrative Embodiment Of The PLIIM-Based Hand-Supportable Area Imager Of The Present Invention Comprising Integrated Speckle-Pattern Noise Subsystem Operated In Accordance With The Seventh Generalized Method Of Speckle-Pattern Noise Reduction Illustrated In Figs. 1I24 Through 1I24C</u>

In Fig. 64A, there is shown a twelfth illustrative embodiment of the PLIIM-based hand-supportable area imager of the present invention. As shown, the PLIIM-based imager 4380 comprises: a hand-supportable housing 4381; a PLIIM-based image capture and processing engine 4382 contained therein, for projecting a planar laser illumination beam (PLIB) 4383 through its imaging window 4384 in coplanar relationship with the field of view (FOV) 4385 of the area image detection array 4386 employed in the engine; a LCD display panel 4387 mounted on the upper top surface 4388 of the housing in an integrated manner, for displaying, in a real-time manner, captured images, data being entered into the system, and graphical user interfaces (GUIs) required in the support of various types of information-based transactions; a data entry keypad 4389 mounted on the middle top surface 4390 of the housing, for enabling the user to manually enter data into the imager required during the course of such information-based transactions; and an embedded-type computer and interface board 4391, contained within the housing, for carrying out image processing operations such as, for example, bar code symbol decoding operations, signature image processing operations, optical character recognition (OCR) operations, and the like, in a high-speed manner, as well as enabling a high-speed data communication interface 4392 with a digital communication network 4393, such as a LAN or WAN supporting a networking protocol such as TCP/IP, Appletalk or the like.

As shown in Fig. 64B, the PLIIM-based image capture and processing engine 4382 comprises: an optical-bench/multi-layer PC board 4394, contained between the upper and lower portions of the engine housing 4395A and 4395B; an IFD (i.e. camera) subsystem 4396 mounted on the optical bench, and including area CCD image detection array 4386 contained within a light-box 4397 provided with image formation optics 4398, through which light

collected from the illuminated object along the 3-D field of view (FOV) 4385 is permitted to pass; a pair of PLIMs (i.e. comprising a dual VLD PLIA) 4399A and 4399B mounted on optical bench 4396 on opposite sides of the IFD module, for producing the PLIB 4383 within the 3-D FOV 4385; a cylindrical lens array 4400 mounted before each PLIM; a pair of beam sweeping mechanisms 4401A and 4401B for sweeping the planar laser illumination beam (PLIB) produced from the PLIA across the 3-D FOV; and an optical assembly configured with each IFD module, including a high-speed electro-optical shutter 4402 disposed before the entrance pupil thereof, which provides a despeckling mechanism that operates in accordance with the seventh generalized method of speckle-pattern noise reduction illustrated in Figs. 1I24 through 1I24C.

LED-Based PLIMS Of The Present Invention For Producing Spatially-Incoherent Planar Light Illumination Beams (PLIBs) For Use In PLIIM-Based Systems

In the numerous illustrative embodiments described above, the planar light illumination beam (PLIB) is generated by laser based devices including, but not limited to VLDs. In long-range type PLIIM systems, laser diodes are preferred over light emitting diodes (LEDs) for producing planar light illumination beams (PLIBs), as such devices can be most easily focused over long focal distances (e.g. from 12 inches or so to 6 feet and beyond). When using laser illumination devices in imaging systems, there will typically be a need to reduce the coherence of the laser illumination beam in order that the RMS power of speckle-pattern noise patterns can be effectively reduced at the image detection array of the PLIIM system. In short-range type imaging applications having relatively short focal distances (e.g. less than 12 inches or so), it may be feasible to use LED-based illumination devices to produce PLIBs for use in diverse imaging applications. In such short-range imaging applications, LED-based planar light illumination devices should offer several advantages, namely: (1) no need for despeckling mechanisms as often required when using laser-based planar light illumination devices; and (2) the ability to produce color images when using white (i.e. broad-band) LEDs.

Referring to Figs. 65A through 67C, three exemplary designs for LED-based PLIMs will be described in detail below. Each of these PLIM designs can be used in lieu of the VLD-based PLIMs disclosed hereinabove and incorporated into the various types of PLIIM-based systems of the present invention to produce numerous planar light illumination and imaging (PLIIM) systems which fall within the scope and spirit of the present invention disclosed herein. It is understood, however, that to due focusing limitations associated with LED-based PLIMs of the present invention, LED-based PLIMs are expected to more practical uses in short-range type imaging applications, than in long-range type imaging applications.

In Fig. 65A, there is shown a first illustrative embodiment of an LED-based PLIM 4500 for use in PLIIM-based systems having short working distances. As shown, the LED-based PLIM 4500 comprises: a light emitting diode (LED) 4501, realized on a semiconductor substrate 4502, and having a small and narrow (as possible) light emitting surface region 4503 (i.e. light emitting source); a focusing lens 4504 for focusing a reduced size image of the light emitting source 4503 to its focal point, which typically will be set by the maximum working distance of the system in which the PLIM is to be used; and a cylindrical lens element 4505 beyond the focusing lens 4504, for diverging or spreading out the light rays of the focused light beam along a planar extent to produce a spatially-incoherent planar light illumination beam (PLIB) 4506, while the height of the PLIB is determined by the focusing operations achieved by the focusing lens 4505; and a compact barrel or like structure 4507, for containing and maintaining the above described optical components in optical alignment, as an integrated optical assembly.

Preferably, the focusing lens 4504 used in LED-based PLIM 4500 is characterized by a large numerical aperture (i.e. a large lens having a small F #), and the distance between the light emitting source and the focusing lens is made as large as possible to maximize the collection of the largest percentage of light rays emitted therefrom, within the spatial constraints allowed by the particular design. Also, the distance between the cylindrical lens 4505 and the focusing lens 4504 should be selected so that beam spot at the point of entry into the cylindrical lens 4505 is sufficiently narrow in comparison to the width dimension of the cylindrical lens. Preferably, flat-top LEDs are used to construct the LED-based PLIM of the present invention, as this sort of optical device will produce a collimated light beam, enabling a smaller focusing lens to be used without loss of optical power. The spectral composition of the LED 4501 can be associated with any or all of the colors in the visible spectrum, including "white" type light which is useful in producing color images in diverse applications in both the technical and fine arts.

The optical process carried out within the LED-based PLIM of Fig. 65A is illustrated in greater detail in Fig. 65B. As shown, the focusing lens 4504 focuses a reduced size image of the light emitting source of the LED 4501 towards the farthest working distance in the PLIIM-based system. The light rays associated with the reduced-sized image are transmitted through the cylindrical lens element 4505 to produce the spatially-incoherent planar light illumination beam (PLIB) 4506, as shown.

In Fig. 66A, there is shown a second illustrative embodiment of an LED-based PLIM 4510 for use in PLIIM-based systems having short working distances. As shown, the LED-based PLIM 4510 comprises: a light emitting diode (LED) 4511 having a small and narrow (as possible) light emitting surface region 4512 (i.e. light emitting source) realized on a semiconductor substrate 4513; a focusing lens 4514 (having a relatively short focal distance) for focusing a reduced size image of the light emitting source 4512 to its focal point; a collimating

lens 4515 located at about the focal point of the focusing lens 4514, for collimating the light rays associated with the reduced size image of the light emitting source 4512; and a cylindrical lens element 4516 located closely beyond the collimating lens 4515, for diverging the collimated light beam substantially within a planar extent to produce a spatially-incoherent planar light illumination beam (PLIB) 4518; and a compact barrel or like structure 4517, for containing and maintaining the above described optical components in optical alignment, as an integrated optical assembly.

Preferably, the focusing lens 4514 in LED-based PLIM 4510 should be characterized by a large numerical aperture (i.e. a large lens having a small F #), and the distance between the light emitting source and the focusing lens be as large as possible to maximize the collection of the largest percentage of light rays emitted therefrom, within the spatial constraints allowed by the particular design. Preferably, flat-top LEDs are used to construct the PLIM of the present invention, as this sort of optical device will produce a collimated light beam, enabling a smaller focusing lens to be used without loss of optical power. The distance between the collimating lens 4515 and the focusing lens 4513 will be as close as possible to enable collimation of the light rays associated with the reduced size image of the light emitting source 4512. The spectral composition of the LED can be associated with any or all of the colors in the visible spectrum, including "white" type light which is useful in producing color images in diverse applications.

The optical process carried out within the LED-based PLIM of Fig. 66A is illustrated in greater detail in Fig. 66B. As shown, the focusing lens 4514 focuses a reduced size image of the light emitting source of the LED 4512 towards a focal point at about which the collimating lens is located. The light rays associated with the reduced-sized image are collimated by the collimating lens 4515 and then transmitted through the cylindrical lens element 4516 to produce a spatially-coherent planar light illumination beam (PLIB), as shown.

<u>Planar Light Illumination Array (PLIA) Of The Present Invention Employing Micro-Optical Lenslet Array Stack Integrated To An LED Array Substrate Contained Within A Semiconductor Package Having A Light Transmission Window Through Which A Spatially-Incoherent Planar Light Illumination Beam (PLIB) Is Transmitted</u>

In Figs. 67A through 67C, there is shown a third illustrative embodiment of an LED-based PLIM 4600 for use in PLIIM-based systems of the present invention. As shown, the LED-based PLIM 4600 is realized as an array of components employed in the design of Figs. 66A and 66B, contained within a miniature IC package, namely: a linear-type light emitting diode (LED) array 4601, on a semiconductor substrate 4602, providing a linear array of light emitting sources 4603 (having the narrowest size and dimension possible); a focusing-type microlens array 4604, mounted above and in spatial registration with the LED array 4601, providing a focusing-type

lenslet 4604A above and in registration with each light emitting source, and projecting a reduced image of the light emitting source 4605 at its focal point above the LED array; a collimating-type microlens array 4607, mounted above and in spatial registration with the focusing-type microlens array 4604, providing each focusing lenslet with a collimating-type lenslet 4607A for collimating the light rays associated with the reduced image of each light emitting device; and a cylindrical-type microlens array 4608, mounted above and in spatial registration with the collimating-type micro-lens array 4607, providing each collimating lenslet with a linear-diverging type lenslet 4608A for producing a spatially-incoherent planar light illumination beam (PLIB) component 4611 from each light emitting source; and an IC package 4609 containing the above-described components in the stacked order described above, and having a light transmission window 4610 through which the spatially-incoherent PLIB 4611 is transmitted towards the target object being illuminated. The above-described IC chip can be readily manufactured using manufacturing techniques known in the micro-optical and semiconductor arts.

Notably, the LED-based PLIM 4500 illustrated in Figs. 65A and 65B can also be realized within an IC package design employing a stacked microlens array structure as described above, to provide yet another illustrative embodiment of the present invention. In this alternative embodiment of the present invention, the following components will be realized within a miniature IC package, namely: a light emitting diode (LED) providing a light emitting source (having the narrowest size and dimension possible) on a semiconductor substrate; focusing lenslet, mounted above and in spatial registration with the light emitting source, for projecting a reduced image of the light emitting source at its focal point, which is preferably set by the further working distance required by the application at hand; a cylindrical-type microlens, mounted above and in spatial registration with the collimating-type microlens, for producing a spatially-incoherent planar light illumination beam (PLIB) from the light emitting source; and an IC package containing the above-described components in the stacked order described above, and having a light transmission window through which the composite spatially-incoherent PLIB is transmitted towards the target object being illuminated.

Airport Security System Of The Present Invention Employing X-Ray Baggage Scanners, PLIIM-Based Passenger and Baggage Identification, Profiling And Tracking Subsystem, An Internetworked Passenger and Baggage RDBMSs, And Automated Data Processing Subsystems For Operating On Collected Passenger And Baggage Data Stored Therein

In Figs. 68A and 68B, there is shown a novel airport security system for carrying out passenger and baggage identification, profiling, tracking and analysis using one or more PLIIM-based object identification and dimensioning subsystems 25' of the present invention.

As shown in Fig. 68A, the airport security system 2600 comprises: (1) at least one PLIIM-based passenger identification and profiling camera subsystem 25', for (i) capturing a digital image of the face, head and upper body of each passenger to board an aircraft at the airport, (ii) capturing a digital profile of his or her face and head (and possibly body) using the LDIP subsystem 122 employed therein, (iii) capturing a digital image of the passenger's identification card(s) 2601, (iii) indexing such passenger attribute information with the corresponding passenger identification (PID) number encoded within the PID bar code symbol 2602 that is printed on a passenger identification (PID) bracelet 2603 affixed to the passenger's hand at the passenger check-in station 2605, and to be worn thereby during the entire duration of the passenger's scheduled flight; (2) a passenger identification (PID) bar code symbol and baggage identification (BID) bar code symbol dispensing subsystem 2606, installed at the passenger check-in station 2605, for dispensing (i) the PID bar code symbol 2602 and bracket 2603 to be worn by the passenger, and (ii) a unique BID bar code label 2607 for attachment to each baggage article 2608 to be carried aboard the aircraft on which the checked-in passenger will fly (or on another aircraft), wherein each BID bar code symbol 2607 assigned to baggage article is co-indexed with the PID bar code symbol 2602 assigned to the passenger checking in his or her baggage; (3) a tunnel-type package identification, dimensioning and tracking subsystem 2610 as shown, for example, in Fig. 31, comprising at least one PLIIM-based PID unit 25' installed before the entry port of the X-radiation baggage scanning subsystem 2611 (or integrated therein), and also passenger and baggage data element tracking computer 2612, for automatically (i) identifying each article of baggage 2608 by reading the baggage identification (BID) bar code symbol 2607 applied thereto at a baggage check-in station 2613 of the airport security system 2600, (ii) dimensioning (i.e. profiling) the article of baggage, (iii) capturing a digital image 2614 of the article of baggage, (iv) indexing such baggage attribute information with the corresponding BID number encoded into the scanned BID bar code symbol, and (v) sending such BID-indexed baggage attribute information to a passenger and baggage attribute RDBMS 2616 for storage as a baggage attribute record, as illustrated in Fig. 68B; (4) an x-ray (or CT) baggage scanning subsystem 2611 (i.e. realizable by any X-Ray Scanning System by Perkin-Elmer Instruments, or other x-ray scanner vendor), installed slightly downstream from the tunnel-based system 2610, for automatically scanning each BID bar coded article of baggage to be loaded onto an aircraft using, for example, x-radiation, gamma-radiation and/or other radiation beams, and producing visible digital images of the interior and contents of each baggage article; (5) the passenger and baggage attribute RDBMS 2616, operably connected to the PLIIM-based passenger identification and profiling camera subsystem 25', the baggage identification (BID) bar code symbol dispensing subsystem 2606, the tunnel-type package identification and dimensioning subsystem 2610, and the baggage scanning subsystem 2611, for

maintaining coindexed records on passenger attribute information and baggage attribute information, as illustrated in Fig. 68B; (6) a computer-based information processing subsystem 2618 for processing passenger and baggage attribute records (e.g. text files, image files, voice files, etc.) as shown in Fig. 68B and maintained in the RDBMS 2616, to automatically mine and detect suspect conditions in such information records, as well as in records maintained in a remote RDBMS 2620 in communication with the processor 2618 via the Internet 2621, which might detect a condition for alarm or security breach (e.g. explosive devices, identify suspect passengers linked to criminal activity, etc.); and (7) one or more security breach alarm subsystems 2622, for detecting and issuing alarms to security personnel 2623 and other subsystems 2624 concerning possible security breach conditions during and after passengers and baggage are checked into an airport.

In the illustrative embodiment, the PID number encoded into each PID bar code symbol assigned to each passenger encodes a unique passenger identification number. Preferably, this number is also encoded within each BID bar code symbol 2607 affixed to the baggage articles carried by the passenger. The PID and BID bar code symbols may be constructed from 1-D or 2-D bar code symbologies. It is also understood that other number systems may be used with acceptable results. In Fig. 68B, there is shown an exemplary passenger and baggage database record 2620 which is created and maintained by the airport security system 2600 of Fig. 68A. Notably, for each passenger boarding a scheduled flight, PID-indexed information attributes 2621 are stored in RDBMS 2618 with BID-indexed information attributes 2622 linked to the PID-indexed information attributes associated with the passenger carrying on the baggage articles. Also, an optional retinal scanner or other biometric scanner may be provided at each passenger check-in station to collect biometric information about the passenger to confirm his or her identity. Such information will also be indexed with the passenger's PID number and stored in the RDBMS 2616 for subsequent analysis.

Operation of the airport security system 2600 will be described in detail below. Each passenger who is about to board an aircraft at an airport, would first go to check-in station 2605 with personal identification (e.g. passport, driver's license, etc.) in hand as well as articles of baggage to be carried on the aircraft by the passenger. Upon checking in with this station, the passenger identification (PID) bar code symbol and baggage identification (BID) bar code symbol dispensing subsystem 2606 issues (1) a passenger identification bracelet 2603 bearing a PID bar code symbol, and (2) a corresponding PID bar code symbol 2607 for attachment to each package carried on the aircraft by the passenger. At the same time, subsystem 2606 creates a passenger/baggage information record 2660 in the RDBMS 2616 for each passenger and set of baggage checked into the system 2600 at the check-in station 2605. Then, the passenger identification (PID) bracelet 2603 is affixed to the passenger's hand at the passenger check-in

station 2605 which is to be worn during the entire duration of the passenger's scheduled flight. Then, the PLIIM-based passenger identification and profiling camera subsystem 25' automatically captures (i) a digital image of the passenger's face, head and upper body, (ii) a digital profile of his or her face and head (and possibly body) using the LDIP subsystem 122 employed therein, and (iii) a digital image of the passenger's identification card(s) 2601. Each such item of passenger attribute information is indexed with the corresponding passenger identification (PID) number encoded within the PID bar code symbol 2602 printed on the passenger identification (PID) bracelet 2603 affixed to the passenger's hand at the passenger check-in station 2605.

Then each BID bar coded article of baggage is conveyed through the tunnel-type package identification, dimensioning and tracking subsystem 2610 installed before the entry port of the X-radiation baggage scanning subsystem 2611 (or integrated therewith), and then through the X-radiation baggage scanning subsystem 2611. As this scanning process occurs, each bar coded article of baggage is automatically identified, imaged, and dimensioned/profiled by subsystem 2610 and then imaged by x-radiation scanning subsystem 2611. The passenger and baggage attribute information items generated by each of these subsystems are automatically indexed with the PID and BID numbers, respectively, of the passengers and baggage, and stored in the RDBMS 2616 for subsequent information processing.

Conventional methods of detecting suspicious conditions revealed by x-ray images of baggage are used (e.g. using an x-ray monitor adjacent the x-ray scanning subsystem 2611), and passengers are authorized to either board the aircraft unless such a condition is detected. In addition, intelligent information processing algorithms running on processor 2618 automatically operate on each passenger and baggage attribute record stored in RDBMS 2616 as well as RDBMS 2660 in order to detect any suspicious conditions which may given concern or alarm about either a particular passenger or article of baggage presenting concern or a breach of security. Such post-check-in information processing operations can also be carried out with human assistance, if necessary, to determine if a breach of security appears to have occurred. If a breach is determined prior to flight-time, then the flight related to the suspect passenger and/or baggage might be aborted with the use of security personnel signaled by subsystem 2623. If a breach is detected after an aircraft has lifted off, then the flight crew and pilot can be informed by radio communication of the detected security concern.

The primary advantages of the airport security system and method of present invention is that it enables passenger and baggage attribute information collected by the system to be further processed after a particular passenger and baggage article has been checked in, using automated information analyzing agents and remote intelligence RDBMS 2620. The digital images and facial profiles collected from each checked-in passenger can be compared against

passenger attribute information records previously stored in the RDBMS 2616. Such information processing can be useful in identifying first-time passengers, as well as passengers who are trying to falsify their identity to gain passage aboard a particular flight. Also, in the event that subsequent analysis of baggage attributes reveal a security breach, the digital image and profile information of the particular article of baggage, in addition to its BID number, will be useful in finding and locating the baggage article aboard the aircraft in the event that this is necessary. The intelligent image and information processing algorithms carried out by processing subsystem 2618 are within the knowledge of those skilled in the art to which the present invention pertains.

Modifications Of The Illustrative Embodiments

While each embodiment of the PLIIM system of the present invention disclosed herein has employed a pair of planar laser illumination arrays, it is understood that in other embodiments of the present invention, only a single PLIA may be used, whereas in other embodiments three or more PLIAs may be used depending on the application at hand.

While the illustrative embodiments disclosed herein have employed electronic-type imaging detectors (e.g. 1-D and 2-D CCD-type image sensing/detecting arrays) for the clear advantages that such devices provide in bar code and other photo-electronic scanning applications, it is understood, however, that photo-optical and/or photo-chemical image detectors/sensors (e.g. optical film) can be used to practice the principles of the present invention disclosed herein.

While the package conveyor subsystems employed in the illustrative embodiments have utilized belt or roller structures to transport packages, it is understood that this subsystem can be realized in many ways, for example: using trains running on tracks passing through the laser scanning tunnel; mobile transport units running through the scanning tunnel installed in a factory environment; robotically-controlled platforms or carriages supporting packages, parcels or other bar coded objects, moving through a laser scanning tunnel subsystem.

Expectedly, the PLIIM-based systems disclosed herein will find many useful applications in diverse technical fields. Examples of such applications include, but are not limited to: automated plastic classification systems; automated road surface analysis systems; rut measurement systems; wood inspection systems; high speed 3D laser proofing sensors; stereoscopic vision systems; stroboscopic vision systems; food handling equipment; food harvesting equipment (harvesters); optical food sortation equipment; etc.

The various embodiments of the package identification and measuring system hereof have been described in connection with scanning linear (1-D) and 2-D code symbols, graphical

images as practiced in the graphical scanning arts, as well as alphanumeric characters (e.g. textual information) in optical character recognition (OCR) applications. Examples of OCR applications are taught in US Patent No. 5,727,081 to Burges, et al, incorporated herein by reference.

It is understood that the systems, modules, devices and subsystems of the illustrative embodiments may be modified in a variety of ways which will become readily apparent to those skilled in the art, and having the benefit of the novel teachings disclosed herein. All such modifications and variations of the illustrative embodiments thereof shall be deemed to be within the scope and spirit of the present invention as defined by the Claims to Invention appended hereto.